# ENERGY-EFFICIENT WINDOW DESIGN THROUGH THE INTEGRATION OF DAYLIGHTING AND ARTIFICIAL LIGHTING IN OFFICE BUILDINGS

BY

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بسم الله الرحمن الرحيم

**_DEDICATED_**

**_TO MY FATHER, MOTHER, WIFE AND MY_**

**_CHILDREN AND TO MY BROTHERS AND SISTERS_**

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# TABLE OF CONTENTS

# LIST OF TABLES

# LIST OF FIGURES

# THESIS ABSTRACT

**NAME:** NAGIB T. AL-ASHWAL
**TITLE:** ENERGY-EFFICIENT WINDOW DESIGN THROUGH THE INTEGRATION OF DAYLIGHTING AND ARTIFICIAL LIGHTING IN OFFICE BUILDINGS
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Lighting systems are known to be the major consumer of energy in buildings regardless of prevailing climates. Energy efficiency in a lighting system can be achieved mainly through the minimization of two variables: the lighting power density and the artificial lighting use. System use can be reduced by the effective integration of daylight with artificial lighting, because daylighting can reduce not only energy consumption but also the lighting internal loads and thus the cooling loads.

The effective integration of the artificial lighting system with daylight occurs when artificial lighting can be controlled as a function of daylighting levels reaching the working surfaces. Large window areas allow more daylight into a space, but they may also allow excessive heat gain or loss, which increases the cooling or heating load and consequently the energy consumption. Designing a window for a space in which there is a balance between daylight provision and solar thermal load would lead to minimum energy consumption in the space.

The main objective of this research is to investigate the energy performance for office buildings due to the integration of daylight and artificial lighting. A base case office building was developed by using the common practice in the Dhahran area. The energy simulation program VisualDOE was used to evaluate the impact of daylight integration on office building energy performance. The results showed a reduction of about 35% of lighting energy consumption and 13% of total energy consumption. The building cooling load was also reduced, which resulted in a smaller air-conditioning system. A parametric analysis was conducted to find the impact of different window design parameters, including window area, height and glazing types, on building energy performance. A design tool in the form of a set of graphs and tables was then developed to assist in energy-efficient window design through integration of daylight and artificial lighting for various window-to-wall ratios (WWRs), heights and glazing types for principal zone orientations in office buildings.

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# ملخص الرسالة

**الإســـــــم: نجيب طاهر الأشول**
**عنوان الرسالة: تصميم النوافذ في المباني الإدارية مع مراعاة ترشيد إستهلاك الطاقة الكهربائية من خلال الدمج بين الانارة الطبيعية و الصناعية في المباني الإدارية**
**التخصـــــص: الهندسة المعمارية**
**تـاريـخ التـخرج: مـــايــو 2008**

تعتبر أنظمة الانارة الصناعية في المباني احد المستهلكين الرئيسيين للطاقة الكهربائية بغض النظر عن المناخ السائد. و يمكن التوصل الى ترشيد في استهلاك الطاقة في أنظمة الإنارة من خلال تقليل كثافة طاقة الإنارة و إستخدام انظمة التحكم في الإنارة و يضاف الى ذلك الدمج الفعال للإنارة الطبيعية مع الصناعية مع الأخذ في الإعتبار أن الانارة الطبيعية لا تسمح فقط بالتقليل من إستهلاك الطاقة و لكن ذلك يؤدي أيضاً إلى إنخفاض في الأحمال الداخلية للإنارة و بالتالي أحمال تبريد أقل.

يمكن التوصل إلى الدمج الفعال للإنارة الطبيعية مع الصناعية عندما يكون هناك الإمكانية للتحكم في مستويات الإنارة الصناعية من خلال التعرف على مستويات الإنارة الطبيعية الواصلة إلى سطح العمل في الفراغ الداخلي. تسمح النوافذ ذات المساحات الكبيرة بإنارة طبيعية أكثر و لكنها في نفس الوقت تؤدي إلى زيادة في الإكتساب أو الفقدان الحراري مما يؤدي إلى زيادة في أحمال التدفئة أو التبريد و نتيجة لذلك زيادة في إستهلاك الطاقة الكهربائية. و يكمن الحل التصميمي الأمثل بتصميم نوافذ بحيث يكون هناك إتزان بين متطلبات الإنارة الطبيعية و الأحمال الحرارية مما يؤدي إلى استهلاك أقل للطاقة الكهربائية في المبنى.

أحد الأهداف الرئيسية في هذا البحث هو التحقق من تأثير دمج الإنارة الطبيعية مع الصناعية على إستهلاك الطاقة الكهربائية بمختلف عناصرها في المباني الإدارية. و لهذا الغرض تم تطوير نموذج لمبنى إداري بناءاً على التطبيق التصميمي الشائع في منطقة الظهران و ذلك من خلال إجراء مسح إستبياني لعدد من المكاتب و الشركات الإستشارية في المنطقة. و في هذه الدراسة تمت الاستعانة ببرنامج محاكاة لحساب الطاقة الكهربائية في المباني: VisualDOE لدراسة تأثير إستغلال و دمج الإنارة الطبيعية على الأداء الحراري و استهلاك الطاقة الكهربائية في المباني الإدارية.

أظهرت نتائج الدراسة إنخفاض واضح في الطاقة المستهلكة بواسطة الإنارة الصناعية بحوالي 35% و كذلك انخفض اجمالي استهلاك الطاقة الكهربائية بحوالي 13% عند دمج الإنارة الطبيعية مع الصناعية في نموذج المبنى الإداري. هذا بالإضافة أن أحمال التبريد في المبنى انخفضت مما يؤدي إلى إستخدام نظام تكييف للهواء بحجم أصغر.

خلال هذا البحث اجريت دراسة تحليلية لعناصر تصميم النافذة المختلفة لغرض التعرف على تأثير هذه العناصر على الأداء الحراري و إستهلاك الطاقة في المباني الإدارية عندما يكون هناك دمج و إستغلال للإنارة الطبيعية. و شملت هذه الدراسة التحليلية نسب متعددة لمساحة النافذة الى الجدار و إرتفاعات متعددة للنافذة و أنواع مختلفة للزجاج. و كنتيجة لهذه الدراسة التحليلية تم تطوير أداة تصميمية مساعدة الهدف منها مساعدة المصممين على أختيار و تصميم نوافذ متوافقة مع متطلبات الإنارة الطبيعية و بأقل إستهلاك للطاقة الكهربائية في المبنى أو الفراغ. هذه الأداة عبارة عن مجموعة من الجداول و المخططات تغطي نسب متعددة لمساحة النافذة إلى الجدار و إرتفاعات متعددة للنافذة و كذلك عدد من أنواع الزجاج و ذلك للتوجيهات الرئيسية للفراغات في المباني الإدارية.

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# CHAPTER ONE

# INTRODUCTION

## 1.1 Background

Throughout history, humans have sought shelter from the environment. During this process they sealed out natural light. People were forced to provide an artificial light source until the invention of the transparent materials, which allowed natural light in while keeping out other environment elements. Over the centuries, humans have progressed from the use of fire, to oil lamps and gas lights, to the use of electric incandescent lamps, and more recently to the use of fluorescent and high intensity discharge lamps **(Abdou, 1997)**.

Daylighting is considered the best source of light for good color rendering, and its quality is the one that most likely matches human visual response. It gives a sense of cheeriness and brightness that can have a significant impact on people **(Li, 2001)**. Daylighting is an important element in modern architecture in creating a pleasant visual environment. Daylighting also makes the interior look more lively and attractive. People desire good natural lighting in their living and working environments. It has been reported that good daylighting can improve occupants' performance and contributes to a healthier working space **(Li, 2002).**

The initial uses of artificial light sources were to eliminate darkness and provide illumination to perform basic tasks. Today, however, with ever-changing environmental demands, the need for improved artificial light sources is even greater. Artificial light fast became an alternative to daylighting, and architects now have the illusion of having total control over interior lighting levels. Their mistake was to overlook the fact that artificial lighting should be used as a supplement to daylighting to provide the required illuminance levels in the built environment; it should not be used as a total replacement because of its inherent energy demands. Such a situation persisted for many years, but recently energy awareness has developed amongst many nations, and it has rapidly become apparent that artificial lighting systems consume large quantities of electricity. Therefore, efforts should be made to reduce such consumption as much as possible and at the same time improve the energy efficiency of lighting systems themselves.

People have become more conscious of the interaction between buildings, energy and the environment. There is a growing concern about energy consumption in buildings and its likely adverse affect on the environment. Efficient use of electricity can have economic and environmental benefits. Artificial lighting is one of the major electricity consuming items in many office buildings. For example, in Hong Kong it has been reported that electric lighting in office buildings accounts for 20-30% of total electricity load **(Li, 2001)**. In the commercial sector 25% of the total electricity used is consumed by lighting systems. The use ranges greatly from country to country, and is due not only to climatic conditions, but also to cultural habits. **Table 1.1** presents the average lighting end-use in commercial buildings for some countries, where it can be noted that developed countries tend to present a higher lighting end-use **(Ghisi, 2005)**.

**Table 1.1** Lighting end-use in commercial buildings in different countries (Ghisi, 2005)

| Country | Lighting end-use % |
|---|---|
| China | 15 |
| Korea | 20 |
| USA | 39 |
| Brazil | 24 |
| Mexico | 30 |
| UK | 30-60 |
| Netherlands | 55 |

Moreover, heat gain due to electric lighting represents a significant proportion of the total building cooling load during hot summer months. Recently, there has been an increasing interest in incorporating daylight in the architectural designs to save energy in buildings. The arguments for daylight are strong from the energy and cost-saving viewpoints. Energy savings resulting from daylighting mean not only low electric lighting expenditure and reduced peak electrical demands, but also decreased cooling energy consumption and potential for smaller air-conditioning plants **(Li, 2001).**

Energy efficiency in a lighting system can be achieved mainly through the minimization of two variables: the lighting power density and the lighting system use. The reduction of the lighting power density, which is the ratio of total lamp wattage in a room to its floor area, can be obtained through the use of energy efficient lamps, (luminaries) and associated equipment. However, it must also be noted that energy efficient equipment does not save energy by itself. A lighting design needs to follow all the steps required for efficiency, and the users' requirements must be considered. In brief, one needs not only energy-efficient equipment, but also an energy-efficient lighting design. The second variable – the lighting system use – could be optimized through the use of control systems and also through the integration of daylight. Such an approach could reduce energy consumption and promote energy efficiency in the building **(Ghisi, 2005)**.

The effective integration of the artificial lighting system and daylight occurs when the artificial lighting system can be switched on or off as a function of daylighting levels reaching the working surface of spaces. Therefore, this work will assess the potential for energy savings on lighting due to the effective integration of daylight with artificial lighting in office buildings.

## 1.2 Statement of the Problem

Air-conditioning and artificial lighting consume significant amounts of the energy supplied to a building; therefore, it is essential that the performance of these systems be optimized in order to achieve energy savings. An important factor that can lead to savings is the amount of daylight entering a room, as this can reduce both the artificial lighting and air-conditioning load at the same time. Large windows allow more daylight into a space, and therefore the use of artificial lighting can be reduced. But large glazed areas may also allow excessive heat gains or losses into the building which increase the air-conditioning or heating load and, consequently, the energy consumption. If the windows are small, then heat gains or losses are lower, but artificial lighting may have to be used during the working day to provide the desired levels of luminance on the working surface. The optimum scenario is to specify a window in which there is an ideal balance between daylight provision and the energy consumed by the artificial lighting and air-conditioning.

### 1.3 Significance of the Study

Since the discovery of oil in Saudi Arabia, a rapid growth in the building construction industry has occurred. In Saudi Arabia, the prime energy in buildings is electricity. Buildings represent the major consumer of energy, with about 71% of the total energy consumption **(SEC, 2003)**. Recently, there is a growing awareness of energy cost and its impact on the nation economy and global emissions. There are many reasons that make energy conservation in buildings a critical issue throughout the world, such as:

- Energy recourses are limited
- The rapid increase in energy cost
- Environmental issues
- Saving energy for the next generations

Energy conservation in buildings can be achieved through many strategies. One of these strategies is the integration of daylight and lighting controls to reduce the energy consumption by lighting systems. Energy savings resulting from daylighting may not only lower electric lighting expenditure and reduce peak electrical demands, but also decrease cooling energy consumption by using smaller air-conditioning plants **(Li, 2001).**

Besides energy savings, windows are essential in the workplace for both environmental and psychological reasons. Windows are strongly preferable in the workplace for access to daylight and an outside view. The desire for natural light rather than electric light is one of the reasons why windows are so important to building occupants. Office workers prefer to be closer to windows, despite problems with glare and reflections on their computer monitors. The biophilia hypothesis states that humans have an intimate need to be in contact with nature; one of the most positive aspects of windows does appear to be the ability to see the outside world, including such things as information about weather conditions **(Menzies, 2005)**.

This study will be very helpful in window design for office buildings in Saudi Arabia to utilize daylight and reduce energy consumption. Its importance lies in the fact that it can be utilized at the early design stage. In Saudi Arabia, limited research has been conducted in the field of daylighting and its implications for energy consumption.

### 1.4 Objectives

Buildings are intended to provide shelter for humans. Their role in any community is social, artistic, and functional. Office buildings have special importance among other building types, as their occupants stay for a long time during working hours. Therefore, these buildings should provide comfort for workers from different aspects, such as thermal and visual comfort, in order to enhance workers' productivity. Artificial lighting in office buildings is a major and conspicuous consumer of electrical energy. Moreover, heat gain due to electric lighting represents a significant proportion of the total building cooling load. Daylight is regarded as the finest source of light, and the energy efficiency and savings argument is strong.

The main objectives of this study are:

1. To investigate the energy performance of office buildings when daylight is integrated with artificial lighting.
2. To develop a design tool to assist in energy-efficient integration design of daylight and artificial lighting for different window areas, heights, glazing types and principal zone orientations in office buildings.

## 1.5 Scope and Limitations

This study will address the effective integration of daylight and artificial lighting and its effect on energy savings. It will focus on the determination of the ideal window design to optimize daylighting and improve energy efficiency in office buildings. Window area, type of glazing, and window height, will be the main factors that affect the selection of an energy-efficient window for principal zone orientations. This research study is limited to the hot-humid climate represented by the Eastern Province of Saudi Arabia.

## 1.6 Research Methodology

Improved daylight penetration into a building to reduce the dependency on artificial lighting may be regarded as one of the easiest ways of improving energy efficiency and, as a consequence, of attaining energy savings and reducing environmental pollution.

In order to accomplish the study objectives, the research methodology consists of the following phases:

1. Literature Review

   1.1. Daylighting

   - Reviewing the historical background of daylighting
   - Understanding of daylight nature, availability, and importance in buildings.
   - Identify the importance of daylight and the impact of daylight on office buildings occupants.

   1.2. Daylighting and Energy Efficiency in Buildings

   - Presenting energy consumption and energy end-use of buildings for different countries throughout the world.
   - Reviewing different research studies to recognize the impact of daylight integration on energy savings.
   - Reviewing window area and lighting control effects on the energy performance.
   - Understanding of daylight impact on the thermal buildings load.

1.3. Dynamic Thermal Modeling Programs

- Overview on Thermal Simulation Programs.
- Selection of the software that will be utilized for the simulation process.
- Overview of the selected program.

2. Computer simulation for daylighting and energy

2.1 Base case model assumption, details and limitations. Identification of model schedules.

2.2 Impact of daylight integration on office building base case on the energy consumption and potential of energy savings.

2.3 Detection of the impact of glazing characteristics and window area and height on the office building energy performance.

2.5 Identification of the potential energy savings likely to be achieved when the integration of daylight with artificial lighting is applied.

3. Results, analysis, and interpretation

3.1 Identification of the optimal window area for principal zone orientations for office buildings for Dhahran, Saudi Arabia.

3.2 Investigation of the influence of glazing characteristics and window configuration on the expected energy savings.

3.3 Developing a tool to assist designers to select a window for a zone in an office building which has the balance between daylight provision and energy consumption of the space.

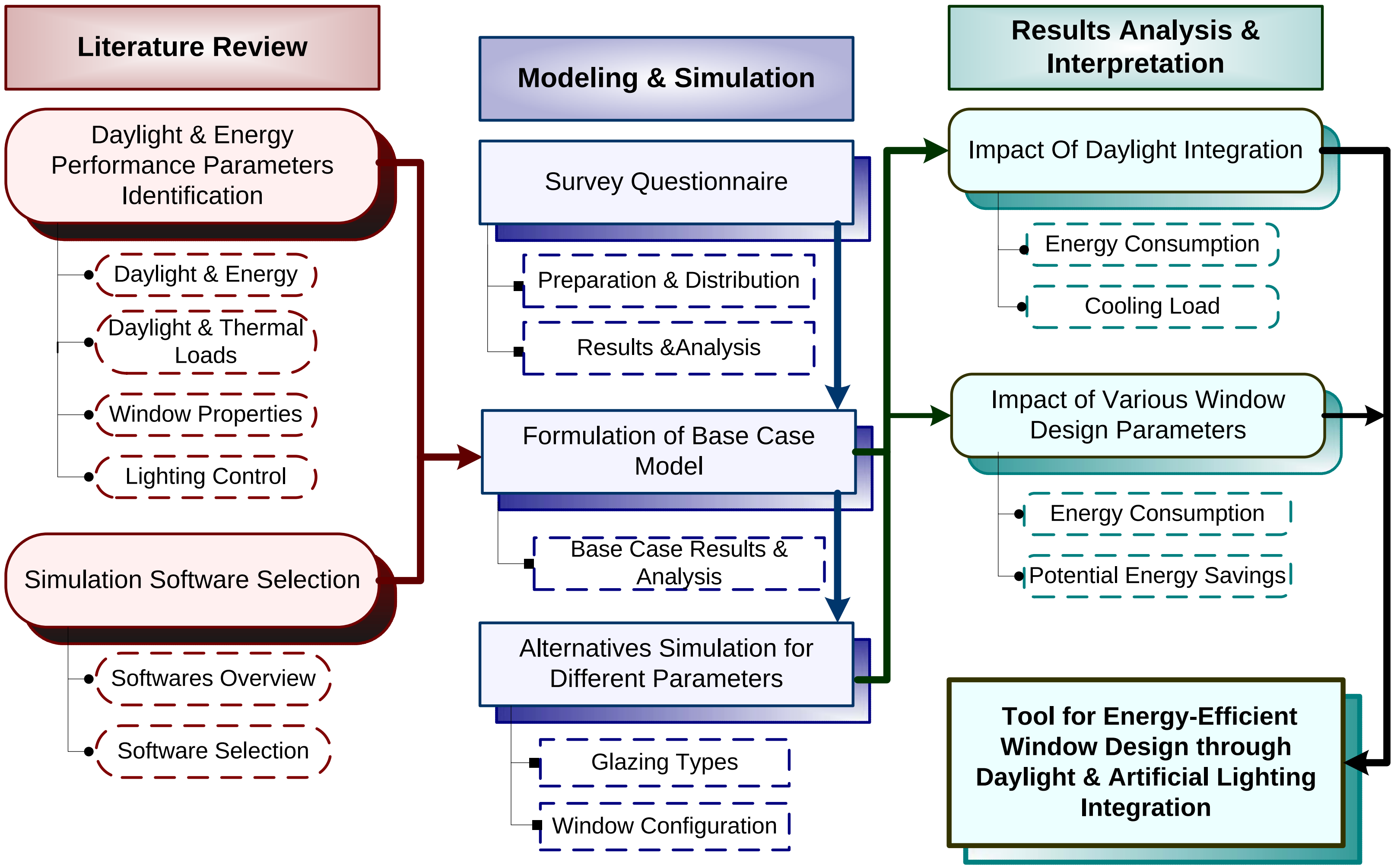



**Figure 1.1** Flow chart of research methodology

# CHAPTER TWO

# LITERATURE REVIEW

Daylighting design can be defined as the design of buildings and lighting systems to make use of sunlight for illuminating the interior space. Some authors reserve the term daylighting for light provided by the sky as distinct from sunlight, which uses direct beams sunlight. In this thesis, the term daylighting will be used to refer to either source of daylight.

## 2.1 Daylighting

The ancients did not have light measuring equipment as we have today; they simply relied on their eyes to perceive light. At night or during cloudy days, their visual tasks could not be performed as well as they could during sunny days. This was perhaps the first indication of the need for basic lighting. The awareness about lighting requirements to perform different visual tasks made people search for sources of light other than the sunlight. They succeeded so well that they started with fire, which, besides providing heat to warm people and to cook food, could also provide light. Daylight was now not the only source of light; a form of artificial light was available. Later developments like whale oil and candles were supposed to provide more photometric comfort and the possibility to work at night. In later years, the electric lamp was developed and, with it, days in the built environment became longer.

### 2.1.1 Historical Background

Organized awareness about good daylighting practice for buildings has a very long history in Europe, and the Romans were pioneers. For example, good daylighting practice is discussed in the classical writings of Vitruvius. Above all, he stressed the importance of properly considering window orientation. Although we now have a far wider variety of glazing materials with which to deal with daylighting tasks, what was written in Roman times still has significant relevance for today. The challenge remains of providing good daylighting without unnecessary heat gains in the overheated season, while the actual techniques used for summer cooling have changed. It can be perceived that the historic daylight solutions are still in use in Roman structures, such as the Pantheon in Rome and the excavated residential buildings at Pompeii (**Baker, 1993**).

It is highlighted that the traditional Islamic architecture had an efficient method for merging the solids of buildings with voids of streets to create a comfortable city with respect to the use of daylight in the urban context **(Mazharuddin, 2000).**

Before artificial lighting became available, it was particularly important to get the daylighting design right. In northern Europe, shortage of daylight, especially in winter, made it necessary to provide relatively large windows, and to secure good daylighting penetration by use of high ceilings and open plan forms. In the southern countries, the dominating needs to control summer overheating, in conjunction with more adequate winter lighting, led to very different window designs and the use of variable plan forms. The courtyard plan was found to provide very agreeable solutions. The sunlight was reflected into buildings from properly placed external surfaces, instead of being allowed to penetrate directly **(Phillips, 2004)**.

The development of architectural styles in the 20th century, which were neither very environmentally not very energetically conscious, tended to overlay the earlier traditions of daylight design. The availability of inexpensive fluorescent electric lighting tended to accelerate the neglect of daylighting design. Many buildings, particularly between 1945 and 1975, have to be evaluated as failures in daylighting design conditions when compared with historic solutions **(Baker, 1993)**.

During the early 20th century, daylight design consciousness rose with the influence of the great architects le Corbusier, Louis Sullivan, Louis Kahn and notably Frank Lloyd Wright. Daylight should be neither ignored nor taken on as an afterthought, but used as an integral element of the functional requirement and aesthetic character of the building (**Mazharuddin, 2000)**.

Nevertheless, the international style changed with the glass boxes of the 50s, 60s, and early 70s, which were almost insensitive to the environment. These buildings created their own thermal and luminous environments, fueled by substantial availability of cheap petroleum-based energy, and they seldom responded to site-specific or climatic information. The glass box began to fall apart when the energy prices increased in the early 70s. Architects and engineers tried to implement any lighting solution that would conserve energy regardless of the impact on visual performance, quality or aesthetics. By the mid-80s and the 90s, quiet reflection based on solid research and experience ousted the previous reaction. Nowadays, there is an exciting production of books, data, methods, and articles concerned with using natural light to its fullest advantage, not only from an economic, but also from visual and aesthetic viewpoints **(Phillips, 2004)**.

### 2.1.2 Daylight Sources and Availability

A predictable pattern of amount and direction of available daylight is produced by the daily and seasonal movements of the sun with respect to a particular geographic location on the Earth. In addition to this predictable pattern, variation results from changes in the weather, temperature, and air pollution. Forty per cent of the solar energy received at the Earth surface is visible radiation. The remaining part is ultraviolet (UV) and infrared (IR) wavelengths. Virtually all of the radiant energy from the sun is converted to heat when absorbed. The amount of usable visible energy in the solar spectrum varies with the depth and condition of the atmosphere through which light passes **(IESNA, 2000)**.

#### 2.1.2.1 Daylight Sources

The quantity and quality of light available for illumination in a building is determined by the regional climatic conditions. Available daylight patterns are modified by factors such as adjacent landforms, vegetation, and structures. The varying light conditions create dramatically different perceptual environments and architectural responses. Daylight can be obtained from three basic resources:

- Diffuse light through clouds or partially cloudy skies
- Direct sunlight through clear or partially cloudy skies
- Reflected light from natural and man-made surfaces

- **The sky as a light source**

As sunlight passes through the atmosphere, a portion is scattered by dust, water vapor and other suspended particles. This scattering, acting in concert with clouds, produces sky luminance. Skies are classified into three types: clear, partly cloudy and overcast. When the sky is not completely overcast, the sky luminance distribution may change rapidly and by a large amount as the sun is alternately obscured, partly obscured, or fully revealed (**IESNA, 2000)**. In the overcast condition, the sky is generally the brightest element in an outdoor scene; light reflected off other surfaces has much lower luminance. Illuminance in the completely overcast condition can exceed 2500 fc. Partly cloudy skies are even more common, constantly changing between direct sunlight and hazy daylight and fluctuating in intensity, distribution, and color temperature **(Egan, 2002)**.

- **Direct sunlight**

Partially cloudy skies are also partially clear. Clear skies and sunlight together perform in a different way from a diffuse overcast sky. In the clear, sunny condition, the sun is the brightest source of light, practically a point source with coherent parallel rays producing sharp shadows. The intensity of the sun differs according to the thickness of the air mass through which light passes, which in turn is influenced by altitude, solar altitude, and atmospheric conditions. The solar illumination at sea level can exceed 10,000 fc perpendicular to the sun rays **(Egan, 2002)**.

- **Reflected light**

The sun illuminates surfaces, creating secondary sources of light. Light-colored surfaces reflecting sunlight are typically the second-brightest source of light in the environment. On a sunny day, they can be the dominant light source in the field of view. Light reflected from the ground may be important in a daylighting design. Such light is, in turn, reflected from the ceiling or walls onto other interior surfaces. On daylighted elevations, the light reflected from the ground normally represents 10 to 15% of the total daylight reaching a window. It frequently exceeds this with light-colored ground surfaces, such as sand or snow. On shaded exposures, it may account for even more of the total light reaching a window, depending on the sky conditions and building design **(IESNA, 2000)**.

Vertical reflected light is most abundant on the shady side of building, where light is reflected from unshaded light-colored walls or facades of adjacent buildings in the sun. Vertical surfaces receive their greatest solar impact at low sun angles, such as in winter time and at high latitudes **(Egan, 2002)**.

### 2.1.2.2 Daylight Availability

Lighting calculation can significantly be more complex for daylighting than for electric lighting. Determination of the illuminanace incident on windows and skylights must take into account the time-varying characteristics of the sky and sun, including the changing spatial relationship between the sun and daylighting openings. Daylight availability refers to the amount of light from the sun and the sky for a specific location, time, date, and sky conditions. Measurements of daylight illuminance by researchers over the past 60 years in locations all over the world have resulted in very similar values. These values were used to determine equations which give available daylight illuminance **(IEA, 2000)**.

Daylight availability data and the equations give mean values, and do not express instantaneous values of illumination. Because of that, measured instantaneous luminance may differ widely from data obtained from calculation methods based on daylight availability. In order to calculate daylight availability at a site, the following values have to be determined **(IESNA, 2000):**

- **Site location:** Specified by a latitude *l* and a longitude *L*. These values can be obtained from any standard atlas or almanac.
- **Time:** Solar time can be determined from standard time (or daylight time) by correcting both for site longitude within the time zone and for equation of time.
- **Solar position:** Position of the sun is specified by the solar altitude and solar azimuth, and it is a function of site latitude, solar time, and solar declination.
- **Sunlight:** The sun is considered to be a point source that provides a constant illuminance at a point on a plane that is normal to the direction of the sun and near the Earth's orbit.

- **Skylight:** The sky-ratio method or the sky-cover method is used to classify a sky. The sky ratio is determined by dividing the horizontal sky irradiance by the global horizontal irradiance. The sky cover method uses estimates of the amount of cloud cover.

#### 2.1.2.3 Potentiality of Daylighting in Saudi Arabia

The amount of external daylight incident on the external surface of the window plane has a significant impact on the utilization of daylight to reduce energy consumption in buildings. As a result, there will be an apparent difference in energy savings from the daylight integration from one location to another. A research study was conducted to investigate the potentiality of natural light if used as a source of internal illuminance in buildings in the Eastern coast of Saudi Arabia. The results of this study demonstrated that, when an average illuminance of 500 lx is required, the vertical illuminance is available at the four orientations for more than 75% of the working year with a room depth of 5 m. If the room depth is changed to 8 m, the average internal illuminance can be achieved for more than 55% of the working year **(Alshaibani, 2001).**

### 2.1.3 The Importance of Daylight

Evidence that daylight is desirable can be found in research as well as in observations of human behavior and the arrangement of office space. Windows that admit daylight in buildings are important for the view and connection they provide with the outdoors. Daylight is also important for its quality, spectral composition, and variability. A review of peoples' reactions to indoor environments suggests that daylight is desired because it fulfils two very basic human requirements: to be able to see both a task and the space well, and to experience some environmental stimulation. Working long-term in electric lighting is believed to be harmful to health; working by daylight is believed to result in less stress and discomfort.

Daylight provides high illuminance, and it permits excellent colour discrimination and colour rendering. These two properties mean that daylight provides the condition for good vision. However, daylight can also produce uncomfortable solar glare and very high luminance reflections on display screens, both of which interfere with good vision. Thus, the effect of daylight on the performance of tasks depends on how the daylight is delivered. All of these factors need to be considered in daylighting design for buildings. Daylight main advantages are discussed in detail below.

#### 2.1.3.1 Occupants' Preferences

**(Galasiu, 2006)** has conducted an investigation for subjective issues related to the utilization of natural lighting in office buildings. Those demonstrated the limitations of current knowledge about how people respond to daylight, and particularly how they respond to automated photo-controlled lighting and shading controls. Current knowledge may be briefly expressed as follows:

- There is a strong preference for daylight in workplaces, associated particularly with the belief that daylight supports better health.
- When both daylight and electric light are used, people overestimate the contribution of daylight to the overall illumination, and the degree of overestimation increases with the distance from the windows.

- Preferred window size probably varies for different settings, but, in general, larger windows are preferred. Window size that is preferred for offices appears to be in the range 1.8–2.4 m in height and somewhat wider than taller to provide a wide lateral view.
- Preferred illuminance levels in offices with daylight vary from one person to another. In addition, desired quantities of additional electric light vary according to the type of task and the distance from the window.

#### 2.1.3.2 Occupants' Health

Many research studies have demonstrated that daylight can help to maintain occupants' health. A study by the U.S. Department of Energy in 2000 found that employees who sit near windows have 20% fewer symptoms common to workers in “sick buildings” **(Solatube International, 2004)**.

Many studies demonstrate that the appropriate use of daylighting decreases the occurrence of headaches, Seasonal Affective Disorder (SAD), and eyestrain. Headaches and SAD are related to insufficient light levels, and they can be reduced when the lighting level is improved by using proper spectral light. However, the number one health problem in offices is eyestrain, and it can be reduced by providing the best spectrum of light for the eye by the proper integration and management of daylighting. When the eye is not allowed to refocus on different distances over long periods of time, the dilating muscles are conditioned to a limited range of perspective, promoting near or far sightedness **(Franta, 1994)**.

A more positive mood for office building occupants can be another important effect of daylighting. An improved mood can result in increased job satisfaction, work involvement, motivation, organizational attachment, and lowered absenteeism. In 1988, Clark and Watson found that negative moods are associated with discomfort and distraction, whereas positive moods are associated with the physical setting at work and daily activities such as social interactions among employees **(Edwards, 2002)**.

A report in The Management Review in October 1999 stated that the lack of light has been shown to cause Seasonal Affective Disorder (winter depression or the winter blues), maladjustment of our body clock (circadian rhythms), and consistent periods of reduced productivity and enthusiasm. The National Commission on Sleep Disorders Research estimates that, in the United States alone, businesses lose more than $150 billion a year in productivity as a result of employee fatigue. One solution is providing a well-lit workspace, with as much natural light as possible **(Solatube International, 2004).**

#### 2.1.3.3 Occupants' Productivity

Office workers strongly believe that lighting conditions are extremely important aspects of their workspace environment. Unfavorable conditions may negatively affect productivity. The definition of productivity as a dependent variable in research on human performance remains a challenge. Increased productivity occurs when people perform tasks more accurately, faster, without loss of accuracy, for longer time periods, and without getting tired **(Abdou, 1997).** Research results in windowless environments vary according to the function of the space. In schools, it has been found that the absence of windows neither harms nor improves student performance, although there is an absence of interest and some absenteeism from the windowless classrooms. In offices there is a widespread opinion that people prefer windows **(Edwards, 2002)**.

In order to include a better quality of light in the building, the Reno Post Office in Nevada was refurbished in 1996. Indirect light was enhanced and better electric lighting was installed. Reports from the first 20 weeks in the new building showed productivity increasing more than 8% and leveling to 6% above the old numbers a year previously **(Romm, 1994)**.

Pennsylvania Power & Light reported that, after completing building upgrades to use more daylight, absenteeism rates dropped 25%, productivity increased 13.2%, and energy costs declined 69%. The original energy payback was calculated to be a 24% annual return on investment. Once the employee productivity and reduced absenteeism were factored in, however, the actual return on investment was approximately 1,000 percent per year. In other words, it was estimated that the lighting retrofit paid for itself not in the 4.1 years estimated, but in just 69 days **(Solatube International, 2004).**

Using an open office layout with integrated daylighting in their offices in Sunnyvale, California in 1983, Lockheed Martin designers successfully increased interaction among the engineers. This increase improved the contract productivity by 15%. Lockheed officials believe that the higher productivity levels pertaining to daylighting helped them win a $1.5 billion defense contract. VeriFone Inc built a new daylit Worldwide Distribution Center near Los Angeles, California, and reported an increase of more than

5% in productivity a year and a half after they started using their new building, and the total product output increased 25%–28% **(Edwards, 2002)**.

In the early 1990s, employees of West Bend Mutual Insurance moved into a new building that gave them personal control over their workstation (temperature, task lighting). This building has artificial lighting on at all times, but the building is designed so that more employees will be close to windows. From the old building to the new one, an increase from 30% to 96% in the number of employees having a perimeter workstation with a window view has been recorded. A 2.8% increase in productivity over the old building was found to result from the new workstations with employee control **(Romm, 1994).**

#### 2.1.3.4 Financial Effect of Daylight

The cost of employees and initial construction of a building are large when compared to the energy and operating costs. For daylighting to pay for itself, the dollar value associated with office worker productivity must increase beyond the added cost of implementing daylighting technology**.** Many companies have found that the increased dollar value of productivity does indeed outweigh the increased cost of technology, as is illustrated by the following examples.

West Bend Mutual Insurance saw increased profit levels due to improved productivity in their enhanced work environment. West Bend realized that its 2.8% gain in productivity is worth approximately $364,000, with its annual salary base of $13 million. This calculation demonstrates the impact of employee productivity on company profits. Lockheed Martin reported financial savings due to increased productivity by moving some of its offices to a daylit building. Lockheed calculated that "every minute less of wasted time per hour represents a 1.67% gain in productivity… where a 2% increase in productivity equates to $3 million saved (per year)". Construction costs of the new daylit building represented 2% of the total building cost. After that expenditure, 6% of the costs are dedicated to maintenance, and the remaining 92% goes toward employee salaries. Lockheed also reports that it has saved half a million dollars on energy bills and reduced absenteeism **(Edwards, 2002)**.

It is reported in EPRI Journal, July 1998 that according to the Electric Power Research Institute, daylit buildings can result in 10 to 20% higher rental income than those that use only artificial lights. A report in Environmental Design & Construction, May/June 2001, said that energy-efficient building design can significantly increase the value of a property. Because these buildings cost less to operate and maintain, energy savings can go directly to the bottom line – the income of the property. Capitalizing this increased income can add $5 to $6 per square foot to the value of the building **(Solatube International, 2004)**.

## 2.2 Daylighting and Energy Efficiency in Buildings

In this section, previous studies are reviewed to illustrate the impact of integrating daylighting in buildings on the energy consumption. This is done through the illustration of the impact on the overall energy consumption in buildings, and this also includes the effect of daylighting integration on energy consumed by the lighting system in buildings. The role of window area on the energy conservation is also clarified in this part of the study. Lighting control strategies influence energy savings. The impact of daylight on the building loads is examined in this section too.

### 2.2.1 Energy Consumption

This part presents an investigation of energy consumption and energy end-uses of buildings submitted to different activities and located in different countries. The main purpose of such an analysis is to present data showing how energy is used in buildings, identifying those end-uses that are responsible for the highest consumption.

Indonesia, Philippines, Singapore, Malaysia and Thailand are the countries that joined the Association of South East Asian Nations (ASEAN). **Table 2.1,** which is part of the *Building Energy Conservation Project Report*, presents energy end-use for buildings located in those countries **(Ghisi, 2002)**. On average, cooling end-use is about 60.0% of the energy consumption in offices, hotels, hospitals, and supermarkets. Lighting end-use ranges from 20.6% to 22.5% of the energy consumption in offices, hotels, and schools. In the store analyzed in Malaysia, it reaches 46.5%. It can be noted that lighting and cooling together account for most of the energy used in buildings in those countries.

A recent study in Hong Kong has shown that electric lighting in office buildings accounts for 20-30% of total building energy consumption, and it believed that this is a potential for energy savings in buildings **(Lam, 1998)**.

**Table 2.1** Energy end-use in the ASEAN countries

| Building Type | Country | Quantity | End-Use (%) | | |
|---|---|---|---|---|---|
| | | | Cooling | Lighting | Others |
| Offices | Indonesia | 1 | 80.1 | 11.8 | 8.1 |
| | Malaysia | 5 | 68.8 | 23.1 | 8.1 |
| | Philippines | 24 | 61.2 | 22.5 | 15.6 |
| | Singapore | 4 | 49.8 | 24.2 | 26.0 |
| | Average | 34 | 61.6 | 22.5 | 15.5 |
| Hotels | Indonesia | 4 | 57.6 | 18.5 | 23.9 |
| | Malaysia | 3 | 61.1 | 22.8 | 16.1 |
| | Philippines | 8 | 63.9 | 16.2 | 18.2 |
| | Singapore | 2 | 55.4 | 38.6 | 6.0 |
| | Average | 17 | 60.9 | 20.6 | 17.7 |
| Hospitals | Malaysia | 1 | 77.9 | 14.7 | 7.4 |
| | Philippines | 8 | 56.1 | 6.6 | 34.5 |
| | Average | 9 | 58.5 | 7.5 | 31.5 |
| Stores | Malaysia | 1 | 40.1 | 46.5 | 13.4 |
| Schools | Singapore | 1 | 71.0 | 22.0 | 7.0 |
| Supermarkets | Philippines | 4 | 58.9 | 6.6 | 34.5 |

The Commercial Buildings Energy Consumption Survey in the USA 1994 provides a data for energy end-uses for buildings located in the USA which are presented in **Table 2.2**. The energy consumption is presented for five different end-uses, and it can be seen that lighting accounts for most of the energy consumption in most types of buildings **(Ghisi, 2002)**.

**Table 2.2** Energy end-use in the USA

| Building Type | End-Use (%) | | | | | |
|---|---|---|---|---|---|---|
| | Heating | Cooling | Ventilation | Office equipment | Lighting | Others |
| Theatres | 10 | 13 | 14 | 3 | 34 | 26 |
| Schools | 5 | 8 | 11 | 5 | 53 | 18 |
| Hospitals | 2 | 20 | 14 | 4 | 44 | 16 |
| Offices | 3 | 10 | 17 | 21 | 35 | 14 |
| Public and safety | - | 5 | 8 | 5 | 44 | 38 |
| Others | - | 7 | - | 6 | 38 | 49 |

In Egypt, over 55% of the total electricity consumption is attributed to residential, commercial, and institutional buildings. Artificial lighting is estimated to account for 36% of the electricity used in the commercial sector during 1999 and 2000. A significant increase in electricity demand is expected over the next few years with a growth rate of 6.8% **(Abd El Mohimen, 2005).**

In Saudi Arabia, the primary energy consumption in buildings is electricity. In 2007, the energy consumption in building sectors reached about 76% **(SEC, 2007)**. **Figure 2.1** shows distribution of sold energy for the whole Kingdom in 2007. A recent study in Saudi Arabia has shown that electric lighting in commercial buildings accounts for 20% of total building energy consumption **(Hasnain, 2000)**. Therefore, it is not surprising that the government of Saudi Arabia realizes the importance of energy conservation and, as a result, legislation is put in place to conserve energy in new buildings. This initiative should be taken as an incentive for researchers and scientists in the Kingdom to work hard to identify possibilities, means, and strategies to reduce the energy consumption **(Ahmad 2002)**.

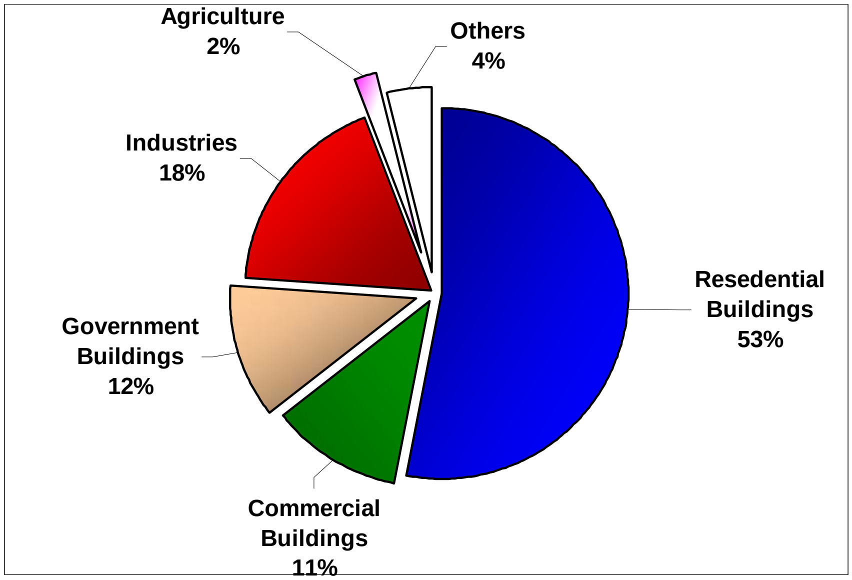



**Figure 2.1** Distribution of sold energy throughout Saudi Arabia (SEC, 2007)

### 2.2.2 Daylight Impact on Energy Savings

**(Santamouris, 1994)** reported the findings of a monitoring campaign in 186 office buildings in Greece regarding energy consumption of the buildings for heating, cooling, and lighting. An assessment of the potential and limitations of different energy conservation techniques was reported. Energy savings for lighting can be obtained either by using more efficient lighting devices or by increasing the natural lighting in the buildings. It was found that, for buildings equipped with fluorescent lamps and operating from 7 A.M. to 5 P.M., the energy contribution from daylighting varies from 40% of the overall lighting load if daylight is provided from one side to 95% if daylight enters from four sides of the buildings. In the case where the building's operation schedule is extended from 7 A.M. to 8 P.M., the energy contribution ranges between 29% and 68% of the overall lighting load.

**(Lam, 1998)** proposed a method to estimate the likely energy savings in electric lighting due to daylighting in air-conditioned office buildings in Hong Kong. It was observed that the estimated energy savings are quite substantial. It was concluded that energy savings for artificial lighting ranges from about 46.5 $kWh/m^2$ for the north perimeter zone to approximately 49.3 $kWh/m^2$ for the south perimeter office. The overall effect of incorporating daylighting is the reduction of electric energy use of 59.7 $kWh/m^2$ per year for all the perimeter zones.

**(Balaras, 2002)** investigated the potential for optimum energy use and conservation of natural resources in representative southern and northern European office buildings using the new European TOBUS methodology and software for office building refurbishment. It was reported that there is a high potential in the reduction of energy consumption for artificial lighting by utilizing daylight in the offices along the perimeter of the building. The percentage of annual hours not needing artificial lighting in two buildings in Greece was estimated to range between 24 and 67% for office spaces with a south orientation, 42 and 48% with a north orientation, 20 and 61% with a west orientation, and 14 and 38% with an east orientation.

**(Bodart, 2002)** evaluated the impact of lighting energy savings on global energy consumption in office buildings. This evaluation comes from an integrated approach combining the daylighting and the thermal aspects. The study was based on simulation results through several façade configurations for the four main orientations and three combinations of internal wall reflection coefficients. It concluded that the potential of global primary energy savings (heating, cooling, humidification, and lighting) by taking into account the daylighting availability is around 40% for the glazing usually used in office buildings in Belgium. These savings could rise to 50% for high performance glazing.

**(Galasiu, 2002)** presented the monitoring results of a field experiment conducted over the course of one year in two side-by-side occupied offices to investigate the impact of various configurations of manually-operated Venetian blinds on the performance of a commercial photo sensor that controlled continuous dimming lighting control system. The performance indicators considered were the electric energy consumption and the illumination level in the space. The results showed that, under clear sky and with no blinds, the lighting control system reduced the lighting consumption on average by 50 to 60% when compared to lights fully on from 6 AM to 6 PM.

**(Li, 2003)** presented field measurements on daylighting for a fully air-conditioned daylit corridor. The amount of energy savings due to daylighting was obtained. It was found that monthly energy savings in electric lighting for the daylit corridor ranged from 3.44 to 4.29 kWh/m$^2$ using the present daylighting scheme. The estimated annual saving was 47.2 kWh/m$^2$, representing 65% reduction in energy use for lighting in the corridor.

**(Ghisi, 2005)** presented a methodology to estimate the potential for energy savings on lighting when there is daylight integration with the artificial lighting system. The methodology was developed by using rooms of ten different dimensions and five different room ratios. The energy analysis was performed using the Visual DOE program for the climatic conditions of Leeds in the UK, and Florianopolis in Brazil. Following this, the potential for lighting energy savings was assessed for each room using a method based on Daylight Factors. It was observed that the potential for energy savings on lighting in Leeds ranged from 10.8% to 44.0% over all room sizes and room ratios. In Florianopolis, the potential ranged between 20.6% and 86.2%.

**(Krarti, 2005)** analyzed the effects on artificial lighting savings of building geometry, window area, window type, and perimeter area for four US locations when daylighting is used. As expected, the daylighting aperture—defined as the product of window visible transmittance and window to perimeter floor area ratio—was found to have a significant impact on energy savings from daylighting. Energy savings due to daylighting integration with artificial lighting can reach 70% of the lighting energy consumption.

**(Li, 2006)** conducted field measurements for a fully air-conditioned open-plan office using a photoelectric dimming system. Electric lighting load, indoor illuminance levels and daylight availability were systematically measured and analyzed. It was found that the daily energy savings in electric lighting for the open plan office ranged from 1.1 to 1.7 kWh using the present daylighting scheme. The estimated annual saving was 365 kWh, representing a 33% reduction in energy use for electric lighting under the dimming control in the office.

### 2.2.3 Window Area

Windows may often lead to high energy consumption in a building if not carefully studied. Large window areas may provide good daylight provision and view, but also they allow for large heat gain or loss which will influence the energy consumption of the building. An assessment of the window area on the façade of a building is important at the design stage in order to optimize the energy efficiency, particularly when there is integration of daylight with artificial light. **(Bell, 1995)** presented an analysis of daylight in building design and provided guidance on the design of windows and roof-lights. It was reported that there is a threshold size, below which windows do not provide a sufficient view, depending on how far one is from the window. These critical minimum window sizes are given in Table 2.3 and are for when windows are restricted to one wall. The same minimum window areas are also recommended in the *Code of practice for daylighting* **(BS 8206-2 1992) (Ghisi, 2002)**.

**Table 2.3** Minimum glazed areas for view (Ghisi, 2002)

| Maximum depth of room (distance from window wall) | Minimum area of window in the wall (as seen from inside - %) |
|---|---|
| < 8 m | 20 |
| 8-11 m | 25 |
| 11-14 m | 30 |
| >14 m | 35 |

In an investigation of 280 residential buildings in Hong Kong, **(Lam, 2000)** observed that the window-to-wall ratio (WWR) of living rooms and bedrooms ranged from 15% to 50%; and about 90% of buildings had WWR between 25% and 35%. As for the glass type, single clear glazing was found in 210 buildings (75% of the sample). **(Gratia,**

**2003)** stated that choices of the overall form of the building, the depth and height of rooms, and the size of windows can together double the energy consumption of the finished building.

In a study to evaluate the impact of lighting energy savings on global energy consumption in office buildings through combining daylighting and thermal aspects, **(Bodart, 2002)** reported that the returns coming from the increasing of window area varies according to the glazing visible transmittance. For example, increasing the fenestration area from 16% to 32% can reduce the lighting consumption by 12% for a glazing of 20% visible transmittance or by 36% for an 81% visible transmittance glazing.

Impacts on daylighting performance were investigated for several combinations of building geometry, window opening size, and glazing type for four geographical locations in the United States **(Krarti, 2005)**. It was stated that for all window types and geographic locations, it is found, as expected, that an increase in the Aw/Ap ratio (window area to perimeter floor area) results in a higher savings of lighting energy use. **Figure 2.2** shows the effects of increasing the Aw/Ap ratio for a set of glazing types when the building has a square geometry (Ap/Af = 0.23) and is located in Atlanta, GA.

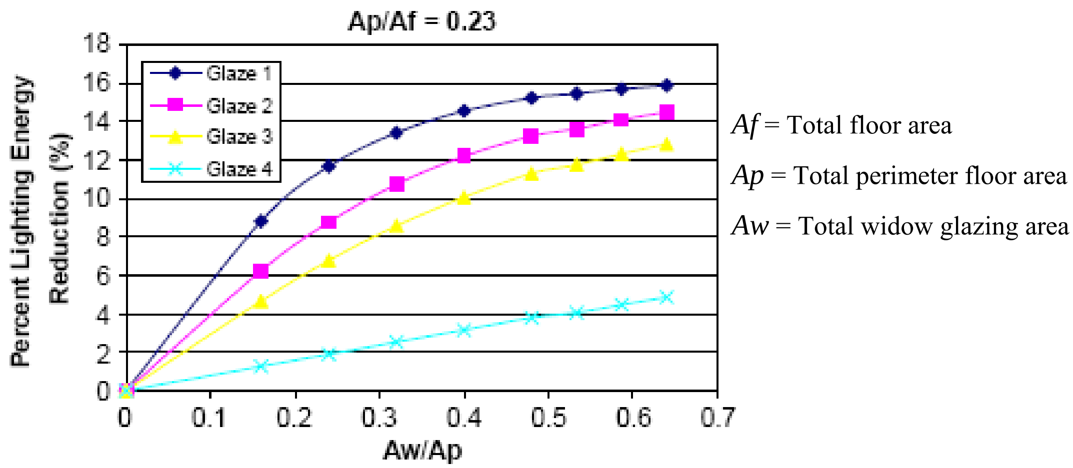



**Figure 2.2** Energy savings relative to window area for a square building in Atlanta, GA (Krarti, 2005)

**(Ghisi, 2005)** studied the potential for energy savings on lighting, using an Ideal Window Area concept and the Visual DOE program for the climatic conditions of Leeds in the UK, and Florianopolis in Brazil. In both cities, it was observed that the Ideal Window Area increases in larger rooms and also in rooms with a narrower width (from room ratio 2:1 towards 1:2). For buildings in Leeds, the Ideal Window Area tends to be larger on the North orientation, as the city is located in the northern hemisphere and the solar thermal load on this orientation is negligible. For Florianopolis, the Ideal Window Area tends to be larger on the East and South orientations, as their solar thermal load is lower. The Ideal Window Area also has a tendency to be smaller on the West orientation, as this is the orientation under the most severe solar condition.

In a study on the effects on artificial lighting savings of building geometry, window area, window type, and perimeter area for three locations in Egypt when daylighting is used, **(Abd El Mohimen, 2005)** reported that for all window types and geographic locations, it is found that an increase in the $A_w/A_p$ ratio (window area to perimeter floor area) results in a higher savings of lighting energy use. In addition, it was found that higher visible transmittance for the glazing leads to increased daylighting benefits and higher savings in electrical lighting use.

A study in Hong Kong on the potential of energy savings in electric lighting, due to daylighting in air-conditioned office buildings, stated that when WWR (window-to-wall ratio) is changed from 44% to 70%, there is an increase in the solar heat gain, ranging from 17.4 kWh/m$^2$ for the north perimeter office to 29.3 kWh/m$^2$ for the west. The larger window area provides more natural light, and it slightly reduces the amount of perceptible heat gain from electric lighting **(Lam, 1998)**.

A study to optimize the relationship between window size, space dimensions and daylight with regard to the energy consumption of the space was performed by **(Ghisi, 2001).** It was concluded from this work that the Ideal Window Area tends to be larger on the orientations where energy consumption is lower due to the reduced solar radiation reaching them. It was also observed that the larger the room and the smaller the façade, the larger the Ideal Window Area.

### 2.2.4 Impact of Glazing Characteristics

**The Windows and Daylighting Group** of the **Lawrence Berkeley National Laboratory (LBNL)** provides the International Glazing Database (IGDB), which is a publicly available collection of data for more than 1000 glazing products from manufacturers all over the world. Each record contains detailed spectral optical data, thermal data, structural details, description and product information. The data is sufficient to design glazing systems and windows, and to perform accurate energy performance calculations.

Many research studies address the influence of glazing types on the energy performance in buildings. The following paragraphs describe briefly the results obtained from various examples of research studies.

A research paper **(Abd El Mohimen, 2005)** summarizes the results of a simulation analysis to determine the impact of window size, building size, daylighting control, and glazing type on daylighting performance for three geographical locations in Egypt. Five different glazing types with varying light transmittance were selected and analyzed. The results analysis shows that larger windows (i.e. higher values of WWR) lead to an increase in total building electrical energy use for all glazing types. The increase is significant for glazing with high solar heat gain coefficients (i.e. clear and reflective single-pane glazing). The annual electricity use of the prototypical office building is reduced for all glazing types and for all window-to-wall ratios when daylighting is incorporated.

**(Bodart, 2002)** evaluated the impact of lighting energy savings on global energy consumption in office buildings. Nine glazing types were analyzed, and their visible transmittance varies from 0 to 81%. The artificial lighting consumption increases when the visible transmittance value decreases. However, this consumption variation is not linear. In this analysis the lighting calculations are based on 500 lx and, when this level is reached, the artificial lighting consumption is no longer affected by any increase in the daylighting availability.

In Belgium, research was conducted on the design of low-energy office buildings. Considering glazing types, this study concluded that high visible transmittance glazing is beneficial for the reduction in lighting energy consumption. However, beyond a certain value, the benefits decrease **(Gratia, 2003)**.

A simplified analysis method was provided to evaluate the potential of daylighting to save energy associated with electric lighting use. Particularly, impacts on daylighting performance were investigated for several combinations of building geometry, window opening size, and glazing type for four geographical locations in the United States. Different glazing types and window areas were modeled in combination with four geometries. The results showed that the transmittance of the windows has a significant impact on daylighting-induced energy savings. As the transmittance of the glazing is reduced, the lighting energy savings are also reduced. The tinted windows resulted in energy savings that were linearly dependent on window area, contrary to the diminishing returns behavior observed with the higher transmittance glazing **(Krarti, 2005)**.

### 2.2.5 Daylight Impact on Building Thermal Load

It is a fact that energy cannot be created or destroyed; only its form can be changed. As a result, energy which operates artificial lighting systems is changed into light and heat. It must also be understood that the visible spectrum, with wavelengths between 380 and 780nm, is situated within the thermal radiation range **(Ghisi, 2002)**. In this way, part of the light will also become heat. The heat generated by artificial lighting systems that have to be removed by mechanical cooling is called "lighting cooling load," i.e. it is the heat produced that has to be removed to keep comfort levels, and "lighting heating load" when the heat helps to maintain comfort levels. Lighting load is usually presented as a percentage of the total heating sources in the building, natural or artificial, and therefore depends on many factors, such as weather conditions, wattage installed in the building, area of windows, and the fabric of external walls and roof, number of users, etc.

Daylight aids decrease the electricity use and the associated perceptible cooling load due to artificial lighting. Therefore, proper daylighting designs can contribute to smaller air-conditioning systems and can lower the peak power demand of buildings. In other words, energy savings resulting from daylighting mean not only low electric lighting and reduced peak electrical demands, but also reduced cooling loads and the potential for smaller heating, ventilating and air-conditioning (HVAC) plants **(Li, 2005).**

It is found that approximately 30% of the cooling load is due to artificial lighting through simulations of a specific building located in Orlando, in the USA, **(Parker,**

**1997)**. In general, the heat produced by artificial lighting is responsible for 15% to 20% of the total building cooling load **(IESNA, 2000).**

**(Li, 2005)** reported that the peak cooling load reduction for each month with and without daylighting designs do not differ much; they vary from 379 kW in August to 492 kW in March. Without daylighting controls, the annual peak load occurred at 14:00 on15th August. When daylighting controls were in operation, the annual peak load appeared at 17:00 on 17th August.

In a study on the energy savings of office buildings by the use of semi-transparent solar cells of windows in Japan, it was observed that without lighting control, higher solar cell transmittance resulted in a smaller heating load and a larger cooling load because of the increased solar gain through the window. With lighting control, the heating and cooling loads did not follow this trend. The larger the WWR was, the larger the heating and cooling loads were. The justification is that larger window area resulted in larger U-value through the building fabric, which caused the increase of heat losses or gains. The larger window size also caused the increase of the solar heat gain in the summer **(Miyazaki, 2005).**

**(Gratia, 2003)** reported that energy radiated by lighting with incandescence corresponds to 80% of energy converted, against 50% for a fluorescent lighting. After a period of time, the heat storage capacity of surrounding materials is saturated and the temperature of the room increases. This can be minimized by the use of natural light.

Besides reducing internal gains, the use of daylight makes it possible for energy consumption reduction.

The influence of the coupling between daylight and artificial lighting on thermal loads in office buildings in France was assessed **(Franzetti, 2004).** The results showed that, without utilization of the natural light, the cooling needs are more essential than the heating needs. Cooling is used to evacuate the internal loads, which are mainly due to lighting in the hot period (**Figure 2.3)**. This implies a large reduction of all energy needs (except heating needs) when daylight is valorized even by a basic light control device.

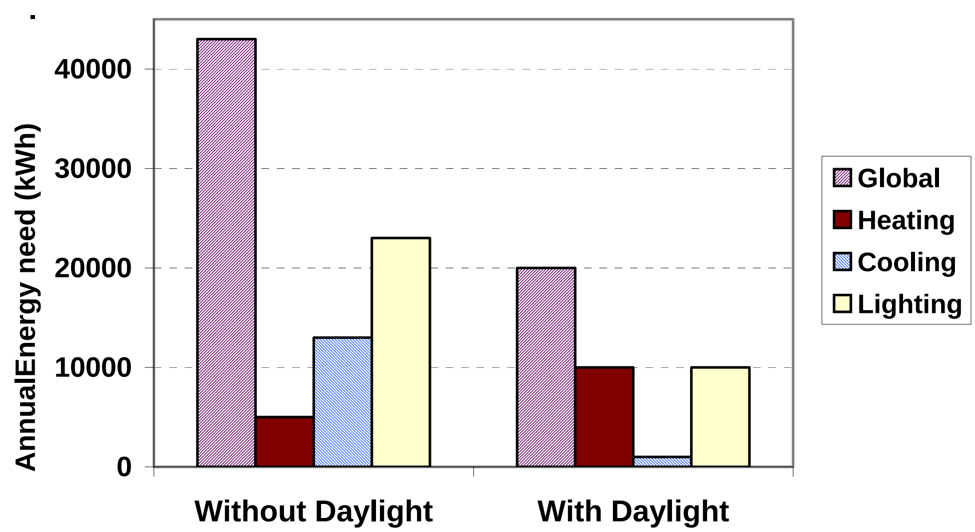



**Figure 2.3** Annual energy needs (kWh) (Franzetti, 2004)

**(Lam's, 1998)** study, regarding daylighting and energy analysis for air conditioned office buildings, reported that reduction in the sensible heat gain from artificial lighting due to daylight integration is about 32.3 $kWh/m^2$ for on-off lighting control and 35 $kWh/m^2$ for top-up lighting control.

**(Abd El Mohimen, 2005)** presented an analysis of daylighting benefits for office buildings in Egypt, and the results showed that, besides reducing the total annual building energy use, daylighting reduces the peak cooling loads and the peak electricity demands. In Cairo, the reduction is estimated to be 15% for peak electricity demand and 7% for peak cooling load when the prototype office building has clear single-pane glazing and a window-to-wall ratio (WWR) of 20%.

### 2.2.6 Lighting Control

Lighting control can be defined as all techniques by which the lighting system will be operated, and it covers both manual and automatic controls. The control strategies should be decided when the lighting design starts, because the control scheme must be appropriate to the light source **(IESNA, 2000)**. The main advantages of using lighting control are

1. Energy management:
    - Reduced energy used.
    - Reduced air-conditioning costs.
    - Longer lamp and ballast life.
2. Aesthetics: provide the ability to change space functions and can create an emotional appeal.

#### 2.2.6.1 Energy management strategies

**IESNA** suggests two main energy management strategies that can be applied:

1. Predictable Scheduling: this is where activities in a building occur routinely during the day; luminaries throughout the space can be operated on a fixed schedule. These strategies are particularly effective when work schedules are defined for the entire area. Such strategies can reduce energy by as much as 40% by eliminating energy waste caused by lights operating in unoccupied spaces.
2. Unpredictable Scheduling: these strategies are used where many events are unpredictable and unscheduled, such as staff meetings, vacations, and business trips. These strategies using occupancy/motion sensors have yielded energy savings of over 60% in some areas.

#### 2.2.6.2 Lighting Control Techniques

According to **(IESNA, 2000),** two types of daylighting controls are generally utilized to reduce electrical lighting use in buildings, namely:

1. Continuous dimming controls: The illuminance in each space can be varied smoothly and continuously to dynamically match visual requirements. Dimming control can be well-suited to daylighting applications. However, the dynamic range of daylight is much larger than it is for electric lighting, and so precautions have to be applied in choosing the suitable dimming control and sensitivity setting.
2. Switching controls: Lighting loads are switched on and off. This switching can be done manually with a simple wall box switch, remotely via relays or switchable circuit breakers, by control systems or by occupancy sensors. A different way to

achieve switched light levels is through light level switchable ballasts. Rather than switching between lamps, the light level switchable ballast can reduce the light from all lamps in the luminaire.

#### 2.2.6.3 Lighting Control Impact on Energy Savings

Many research studies have analyzed the impact of lighting control on energy consumption in buildings. The following paragraphs will focus on the results of some of those studies.

For three locations in Egypt, the control strategy has a considerable effect on the performance of the daylighting system, as evident by the variation of the coefficient *b*. This indicates the daylighting availability during building operating hours, and it represents the percent of time in a year that daylighting can provide the desired illuminance set-point level within the perimeter areas of the building. Thus the coefficient *b* indicates the maximum possible savings of electrical lighting achievable by incorporating daylighting. For stepped controls, the potential savings in lighting energy use increases with the number of steps **(Abd El Mohimen, 2005)**.

**(Li, 2001)** made field measurements of daylighting in an air-conditioned office building in Hong Kong, just below 20% and about 30% of the time, and he reprted that an indoor illuminance of 500 lx can provide daylight for the north and south–facing offices, respectively, under an on-off control. He recorded that with daylighting controls, substantial lighting energy savings can be found. The maximum lighting load did not exceed 180 W. The savings were due primarily to the dimming controls, occupancy sensors during lunch-time, and a small amount from electronic ballasts.

Field measurements were conducted on daylighting for fully air-conditioned daylit corridors. Electric lighting load, brightness of the fluorescent luminaries, daylight illuminance levels, and the room parameters affecting daylighting design were recorded and analyzed. The analysis results have showed that the energy savings in electric lighting were about 70% by using a dimming system to control the lighting **(Li, 2003).**

**(Onaygil, 2003)** evaluated the energy saving via a daylight-responsive lighting control system for an office building in Istanbul. The results demonstrated that the energy saving obtained by the daylight-responsive lighting control system shows differences according to the months and seasons. Energy saving which is only 20% in December increases to 47% in June and July. Energy saving is 21% in winter but 35% in spring and 45% in summer. Energy saving is 35% on clear days but 16% on overcast days. Interestingly, energy saving on mixed days is approximately the same as on clear days.

**(Li, 2006)** presented field measurements for a fully air-conditioned open-plan office using a photoelectric dimming system. He measured and analyzed the electric lighting load, indoor illuminance levels and daylight availability. He presented the general features of the results, such as electric lighting energy savings and transmitted daylight illuminance in the forms of frequency distributions and cumulative frequency distributions. He found that energy savings in electric lighting were over 30% by using the high frequency dimming controls. The results from the study would be useful and applicable to other office spaces with similar architectural layouts and daylight linked with lighting control systems.

Although many studies showed that lighting control is highly beneficial in terms of savings in the electric lighting system, several studies showed that there are some restrictions in applying lighting control systems. This is related to occupants' preferences and practical applications of these systems.

**(Littlefair, 1999)** has reported that a problem with lighting control has been the user reaction to its operation. People do not like automatic controls which switch lights on when they could have been off under manual control. In spaces like offices, classrooms, and residential accommodation, switching on should be done manually, even if a daylight-linked automatic switch-off is offered. In a series of surveys of lighting controls in offices, where photoelectric controls had been installed, it was reported that they had been disconnected **(Slater, 1996).**

**(Littlefair, 1999)** has reported that a special problem with photoelectric switches is the rapid switching of lights on and off when daylight levels happen to fluctuate around the switching illuminance. This can annoy occupants and reduce lamp life. Photoelectric dimming control, although more expensive and more complicated to install, should save more energy. However, problems have been reported. These include poor operation of the system when a single photocell controls a wide area of the building with different daylight levels in different locations, as well as inappropriate control algorithms which cannot maintain the required illuminance on the working surface.

**(Ehrlich, 2001)** has admitted that the use of photo-sensor-based lighting controls has been generally unreliable for two reasons: (a) considerable effort is required to properly place and calibrate the photo-sensor system; and (b) the unreliability of such control systems constitutes a significant market barrier preventing widespread acceptance of daylight dimming controls in commercial buildings.

Regarding commissioning of lighting controls, **(Littlefair, 1999)** reported that this is important because, if the system does not perform properly, there will be not only poor energy savings, but also occupant complaints and ultimately system disconnection.

## 2.3 Summary of Findings

Daylight practice awareness has been developed for a long time in different cultures around the world. Today, daylight is essential in building design because not only does it provide pleasant and healthy spaces but also it has a significant impact on energy saving in buildings. Daylight can be acquired from three main sources: diffuse light, direct light and reflected light.

In order to utilize natural light appropriately in buildings in a specific location, daylight availability has to be predicted. The following main values have to be determined when daylight availability calculation is performed: site location, time (solar time), solar position, sunlight, and sky light.

Research studies have revealed that daylight has great influence on both buildings occupants and building systems performance. Natural light can help in improving occupants' health, as verified by many studies. Daylight can reduce the occurrence of headache, Seasonal Affective Disorder (SAD), and eyestrain. In addition, an appropriate utilization of daylight would increase the office buildings occupants' productivity, which has been demonstrated in many studies.

When energy consumption is reviewed in different countries, it has been noticed that the lighting system in commercial buildings is one of the major end-use consumers that is responsible for high consumption. Many studies reported that the use of daylight in buildings can significantly increase energy savings. Energy savings percentage resulted from daylight integration varies from one location to another and with orientations of spaces, and this percentage can reach more than 75%.

Window area has been regarded as a major parameter to achieve energy-efficient window design. It is reported that the larger the window, the higher the illumination level. Although increasing the window size can lead to high potential energy savings, cooling load in buildings can apparently be influenced. Research results have shown that daylight can reduce electricity use and the associated perceptible cooling load due to artificial lighting. As a result, smaller air-conditioning systems and lower peak power demands can be achieved through the proper daylighting design.

Lighting control is a major component when daylight is integrated with artificial lighting. Significant energy savings can be obtained when lighting controls are applied. Two main types of lighting controls can be installed in buildings, namely: continuous dimming controls and switching controls.

## 2.4 Dynamic Thermal Modeling Programs

The following is a brief review on the growth and application of computer programs used to evaluate thermal and energy aspects of a building performance.

Architects and building services engineers have been assisted by the introduction of computer programs for building simulations in order to achieve a better thermal and energy performance in buildings, as they facilitate the assessment of building components and use. In the early days, manual calculations were likely to result in oversized plant and system capacities, inducing an inadequate energy performance.

Since many essential decisions related to building physics are taken at the early design stage, the thermal performance of a building should be assessed. Simplified methods are used for immediate compliance purposes in many countries where designs are to meet prescriptive standards. Detailed energy simulation programs are required to accurately simulate the thermal performance, with additional flexibility to define design trade-offs for cost effectiveness, yet complying with performance-based standards.

According to **(Hong, 2000)**, building simulation started in the 1960s and became an important subject within the energy research community in the 1970s, when most of the research was committed to fundamental theory and algorithms of load and energy estimation.

Following the oil crisis in the early 1970s, countries like the USA and the UK allocated resources to the development of projects on energy conservation and computer simulation, with programs such as DOE-2 and ESP-r. At the beginning of the 1990s, building professionals were stimulated by growing concern about environmental matters, such as global warming and the damage of the ozone layer, to try to reduce energy consumption and its negative impact on the environment. Therefore, building simulation programs started being used in professional practice and many programs were developed world wide, some with specific objectives.

In order to apply new technologies and evaluate innovative ideas to increase the energy savings in their planned designs, many detailed simulation tools are currently available to assist designers. Detailed energy simulation tools utilize mathematical models to calculate building heat gains or loss (annual and peak), space heat and cooling load, evaluate indoor thermal conditions, and predict energy performance of buildings. Detailed simulation tools carry out their calculations on hourly or sub-hourly bases for better consideration of the dynamic interactions between all thermal-based elements associated with comfort and energy consumption, including the building envelope, HVAC systems, lighting and control devices **(Hong, 2000)**.

Due to continuous development and improvement of simulation programs, it is not easy to classify them. Many building simulation tools are listed at the U.S. Department of Energy (DOE) web directory (http://www.eren.doe.gov/buildings/tools_directory).

### 2.4.1 Overview on Thermal Simulation Programs

Considering the accuracy and ability of handling the dynamic behavior of buildings and its systems, the most common detailed thermal simulation softwares are DOE-2, ESP-r BLAST, and EnergyPlus. On the other hand, in order to achieve final results with acceptable accuracy, substantial data input is usually needed.

For example, the ESP-r program, which was developed and distributed by an association primarily based at the Energy Systems Research Unit, University of Strathclyde, allows an in-depth consideration of the factors which affect the energy and environmental performance of buildings. The ESP-r system has been the subject of constant developments since 1974, and it allows the designer to investigate the interaction between the form of the building, fabric, air flow, plant and control. ESP-r is based on a finite-volume conservation approach, in which a problem is transformed into a set of conservation equations which are then integrated at successive time-steps in response to influences of climate, occupant and control system **(ESRU, 2000).**

DOE-2, a public domain program, was developed by the Simulation Research Group at Lawrence Berkeley Laboratory (LBL). The DOE-2 program, whose development was sponsored by the US Department of Energy, performs an hourly simulation of the building thermal performance, based on a description of the geographic location and building orientation, building materials and envelope components (walls, windows, shading surfaces, etc.), operating schedules, HVAC equipment and controls, utility rate schedule, building component costs, and hourly weather data **(Winkelmann, 1993).** It was first released in 1979 and has since been widely used in the USA and in more than forty countries **(Hong, 2000)**. The DOE-2 program can also be utilized to analyze energy efficiency of given designs or efficiency of new technologies.

Both DOE-2 and ESP-r require time to build a model and also to carry out the simulation because they are based on a UNIX® operating system, which may be a constraint. For this reason, some adaptations, such as adding interfaces to make the DOE-2 program more friendly, were undertaken by the private sector in the USA. As a result of this, a commercial version with a graphic interface VisualDOE was developed by Eley Associates (1995) **(VisualDOE Manual, 2004).** It utilizes the DOE-2.1E hourly simulation tool as the calculation engine, so that energy use and peak demand are accurately evaluated on an hourly basis, but it works with the WINDOWS® operating system.

BLAST (Building Load Analysis and System Thermodynamics) is a set of computer programs for calculating heating and cooling energy consumption in buildings, and for analyzing the energy costs. BLAST was established by Department of Mechanical and Industrial Engineering, University of Illinois at Urbana Champaign and supported by the U.S. Department of Defense (DOD). BLAST can be used to investigate the energy performance of new or retrofit building design options.

The load calculation method is the main difference between DOE-2 and BLAST. The DOE–2 uses a room weighting factor approach, while BLAST uses a heat balance approach. With many capabilities of the two and new added capabilities, a new building performance simulation program “EnergyPlus” was developed to combine the best capabilities and features of the two programs **(Crawley, 1999)**. The major improvement in the EnergyPlus is the integrated solution of loads, system and plant.

### 2.4.2 Simulation Software Selection

Professionals have difficulty in choosing the appropriate program to perform their analysis. It is not an easy task to find the suitable program when detailed simulation methods are required, even though many energy simulation programs are currently available. It is most likely hard to suggest a clear procedure for selecting a simulation program that is suitable for everyone. Many factors, such as accuracy, sensitivity, speed and cost, reproducibility, usability, input complexity, output quality, and weather data availability are generally considered during the selection process **(ASHRAE, 1997)**. Other factors associated with the users should also be considered. These factors can be classified into three main groups: the need or the purpose corresponding to the program capability, the financial resources (to purchase, training, use, and maintain the software), and the availability of existing computer facilities **(Hong, 2000)**.

Many programs have been reviewed. Among these programs the VisualDOE program was selected to be used in this work because of the following factors:

- It has been widely validated for accuracy and consistency.
- It offers a great capability for simulating a wide range of design features and energy conservation measures, including the integration of daylight with artificial light.
- It provides the ability for rapid development of energy simulations, reducing the time required to build a DOE-2 model. It specifies the building geometry much faster than other comparable software, making VisualDOE useful for schematic design studies of the building envelope or HVAC systems.
- VisualDOE also implements the daylighting calculations from DOE-2, making it possible to evaluate the integration of daylight with the artificial lighting system.
- The availability, sufficient training, and capability to maintain the program is another reason in the selection of VisualDOE.

### 2.4.3 VisualDOE Simulation Program

VisualDOE 4.0 is a fourth generation Windows™ application that allows architects, engineers and energy analysts to evaluate the energy savings of building design options. The program covers all major building components, including building envelope, lighting, daylighting, water heating, HVAC and central plant. VisualDOE uses the DOE-2.1E hourly simulation tool as the calculation engine, so that energy use and peak demand are accurately evaluated on an hourly basis. In the past, energy simulation programs such as DOE-2 have been limited to a small circle of energy experts with special expertise. Now the program is widely used in the world for building design and energy conservation studies **(Hui, 2002)**.

VisualDOE is designed so that more advanced calculation engines, such as EnergyPlus, can be used with the interface. The VisualDOE 4.0 user interface is a truly graphic building model, using the standard block shapes, using a built-in drawing tool, or importing DXF files. Pictures of buildings and HVAC system diagrams are produced as the model is created. The model can be verified for accuracy and selecting the right direction, size, shape of thermal zones, windows and other building elements **(VisualDOE Manual, 2004)**.

#### 2.4.3.1 Validation of the DOE Program

Since VisualDOE was the program selected to be used in this work, and because it utilizes the DOE calculating engine, this part presents work published on the validation of the DOE program.

Validations conducted by Los Alamos National Laboratory, Lawrence Berkeley National Laboratory and some universities proved that the DOE-2 program can precisely predict energy use in real buildings. Users will be confident that the results obtained from DOE-2 are reliable for buildings that are accurately modeled by these validations. **(Meldem, 1995)**, **(Diamond, 1986)**, and **(Diamond, 1981)** provide more information about such validations. One must assume that user experience of the program is appropriate and essential to getting reliable results.

**(Meldem, 1995)** reported on a validation of DOE-2.1E regarding the thermal analysis of some test houses in Pala, California. Results from simulations using the program were compared with room air temperature measurements to validate DOE-2.1E in a low-mass house and in a high-mass house. To test different aspects of the DOE-2 calculation, four different unoccupied, unconditioned thermal configurations of these houses were considered: unshaded windows, shaded windows, white exterior surfaces, and forced night ventilation. It is reported that the results obtained from DOE-2 agreed well with the air temperature measurement in all cases, with a mean deviation between simulation and measurement ranging from 0.2 to 1.0 degree Kelvin.

**(Winkelmann, 1985)** addressed the validation of daylighting simulation in DOE-2 through the description of the algorithms which simulate hourly-varying interior illuminance, management of windows for sun and glare control, and the operation of electric lighting control systems. DOE-2 daylighting output was compared with the results of scale model illuminance measurements using the Lawrence Berkeley Laboratory. The difference in the ratio is generally less than 15%.

A study was performed on a validation of DOE-2.1E related to the application of daylight dimming systems and the effect of window orientation and blinds on energy savings. The research was carried out using the Daylighting Test Facility (DTF) located in Florida, USA. The energy consumption was compared in two pairs of offices for all four window orientations (north, south, east and west) in order to evaluate the impact of blinds on dimming savings. The study showed that daylight dimming systems can provide major energy savings ranging from 24% to 51% depending on the orientation and whether the office had blinds. The simulation of the offices using DOE-2.1E agreed with measurements to within 17.4%. For offices with no blinds, the percentage difference between measured and simulated energy consumption ranged between –7.9% and 6.0%; and for offices with blinds, it ranged between 3.9% and 17.4% **(Schrum, 1996)**.

**(Zmeureanu, 1995)** analyzed some work related to simulation of buildings and found that the average difference between measured and simulated values of monthly energy consumption lies between 5% and 24%. **(Sullivan, 1998)** showed that the comparison of calculated and measured quantities have resulted in a satisfactory level of confidence that is sufficient for continued use of DOE program. The old DOE2 code (DOE-2.1A) has also been validated for accuracy in Dhahran, Saudi Arabia **(Bahel, 1989).**

**(ASHRAE, 1995)** states that the input building description must be adjusted, and trial runs continued, until the results approximate the actual energy use. It is usually difficult to match the metered energy consumption precisely. In any month, results within 10% to 20% are considered adequate.

#### 2.4.3.2 Daylight Simulation in VisualDOE

A daylighting calculation has been integrated into the DOE-2 building energy analysis computer program which is used by VisualDOE. The program allows users to determine the impact of daylight utilization on energy use, energy cost, and peak electrical demand. This model, in conjunction with the DOE-2 thermal loads and HVAC analysis, determines the energy and cost related consequences of daylight availability, site conditions, window management in response to solar gain and glare, and various lighting control strategies **(Hitchcock, 1995)**.

**(Winkelmann, 1985)** conducted a research study that described the algorithms which simulate hourly-varying interior illuminance, management of windows for sun and glare control, and the operation of electric lighting control systems. Sample DOE-2 daylighting output reports were presented, and the results of program validation against scale model illuminance measurements using the Lawrence Berkeley Laboratory sky simulator were discussed. The daylighting simulation has three main stages:

1) **Daylight factor preprocessor**: For each daylit space, a set of daylight factors calculations are performed for a series of sun positions covering the annual range of solar altitude and azimuth at the specific building latitude. Interior illuminance components are calculated for each room location. The daylight factors are then obtained by dividing the interior illuminance by corresponding exterior illuminance which is stored for later interpolation in the hourly simulation.
2) **Hourly daylighting calculation**: A daylighting calculation is performed during each hour of daylight. The interior illuminance at each reference point is found for each window, by interpolating the illuminance factors obtained by the preprocessor.
3) **Hourly lighting control simulation**: Stepped and continuously dimming lighting control systems are simulated to determine the electrical lighting energy needed to make up the difference, if any, between the daylighting level and the design

illuminance. Finally, the electrical lighting requirements are passed to the thermal calculation, which determines the hourly heating and cooling requirements for each space and for the building as a whole.

A series of reports are provided by the software giving different levels of information on daylighting performance. Careful analysis and interpretation of these reports can enhance the process of achieving a building design that meets the required performance criteria. VisualDOE provides detailed daylight factor summary report for each space in the project that has daylighting. It includes most of the detailed information used by DOE-2 in making daylighting calculations. Space daylighting summary report is also produced to give monthly-average lighting energy reduction, illuminance, and glare for each daylit space. If only one lighting reference point is specified, the entries under REF PT 2 will be zero. Task lighting energy, as determined by TASK-LIGHTING-KW or TASK-LT-W/SQFT, is not considered. Average daylight illuminance, which gives the average illuminance due to daylight for each lighting reference point, is also provided. For each daylit space a report is produced to give the monthly lighting energy reduction due to daylighting for each hour of the day, and for all hours of the day combined (including nighttime hours). The monthly daylight-illuminance frequency-of-occurrence distribution at each lighting reference point is provided. If only one lighting reference point is specified, the entries under REF PT 2 will be zero. **(VisualDOE Manual, 2004)**.

An hourly report, selected by the user from a list of about 200 different thermal and daylighting variables, provides hourly values of daylighting variables for a particular day and space. The user also selects the time periods when the report is printed, allowing, for example, hourly daylighting profiles to be made for typical days at different times of the year **(Winkelmann, 1985)**.

# CHAPTER THREE

# FORMULATION OF BASE CASE MODEL FOR AN OFFICE BUILDING

## 3.1 Introduction

This chapter focuses mainly on the formulation of a base case model for an office building which will represent a base line for the parametric analysis. The base case model includes the determination of the thermal and physical characteristics of buildings, such as geometric shape, building envelope properties, lighting system requirements, and window design parameters.

In Saudi Arabia a dramatic development has taken place in the last few years in the number of office buildings constructed, building construction materials, design and electrical equipments used in office buildings. In order to define the major thermal and physical characteristics of office buildings in Saudi Arabia, a survey questionnaire was developed and distributed among selected main Architectural/Engineering consulting offices (A/E CO) in the Eastern Province in Saudi Arabia. Despite the challenges faced during the conduct of the survey questionnaire, such as the limited time which chief engineers or architects are willing to spend for this job, twelve consultant offices have participated successfully in the survey.

The survey results were collected and analyzed to define the common thermal and physical characteristics. In addition to the survey questionnaire results, standard references were utilized to define parameters that were not obtained from the survey questionnaire. One of the most important elements in energy simulation process is the operation schedules which were determined mainly based on logical judgment and common practice. Once the main physical and thermal characteristics and operation schedules were defined, the base case model was formulated. In order to check the model and to assess its general validity, base case predictions of building energy performance were compared with general office buildings obtained from the literature.

## 3.2 The Survey Questionnaire

A survey questionnaire was carried out to obtain reliable data on the main essential design parameters in office buildings which are required for the simulation process. The selected consultant offices were chosen to represent a good sample of designers and consultant offices working in the local area.

### 3.2.1 The Survey Questionnaire Contents

The questionnaire was primarily divided into five main sections. The first section contains general information regarding the respondent's information, such as name, company, years of experience, and the average number of office buildings designed. The general information about the design offices and respondents provides a good measure about the reliability of the data collected from the survey questionnaire.

The second section includes general office building characteristics, such as geometrical shape, average floor area, number of floors, and air conditioning system type that is generally used in office buildings.

The third section covers information about building envelope construction including exterior wall systems, building material, exterior finishing and roof system. This section also covers the utilization of thermal insulation in the roof and/or wall systems including thermal insulation material and the minimum thermal resistance (R-value) required for the insulation material.

The fourth section details window design elements, and this includes the commonly used glazing type, the number of glazed layers and the recommended window-to-wall ratio (WWR) for the principal orientations.

The last section covers lighting design requirements from different aspects, such as the required illumination level and lighting power density (LPD), and the generally used lighting source type. This section also includes the investigation of the utilization of natural lighting, daylighting integration purpose, and daylight prediction tools. This section also covers the recommended lighting control strategies that can be utilized for the daylight integration with artificial lighting. A copy of the survey questionnaire can be found in **Appendix A**.

### 3.2.2 Data Collection

The questionnaire was distributed among twelve selected (A/E CO) in the Eastern Province including major consultant offices such as SCADO, Saud Consult and Zuhair Faiz. The data was collected by personal meetings with the chief engineer/architect in those firms. After the results were collected, they were then analyzed and presented using a simple frequency approach. The acquired results are summarized and presented in the following section.

### 3.2.3 Results Analysis and Discussion

#### 3.2.3.1 General Information

In the first section, the design consultants are classified into different categories based on their years of experience in office building design. The results showed that consultant offices can be classified into three main categories according to years of experience: with less than 10 years, between 10 to 15 years, and more than 15 years. The survey results showed that 63% of the selected (A/E CO) have more than 15 years of experience in office building design. On the other hand, 25% of these offices have 10-15 years of experience and only 12% have less than 10 years of experience, as shown in **Figure 3.1.**

These results indicate that the survey results are reliable and can be considered as sufficiently accurate, given the years of experience of the respondents.

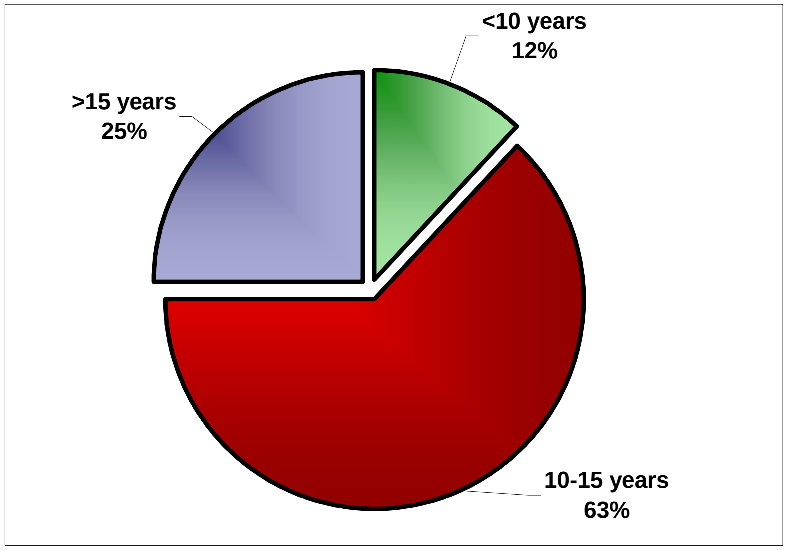



**Figure 3.1** Years of experience of surveyed (A/E CO) in office building design

The selected (A/E CO) responses showed that the minimum number of office buildings that has been designed is ten, whereas the maximum is thirty-five, with an average of twenty-one. These results have demonstrated that the selected consultant offices have sufficient experience in office building design.

#### 3.2.3.2 Building General Information

**Figure 3.2** shows that the common geometry of the office building plan is rectangular (45%) and square (40%), with the majority of 4-10 floors height. These results have provided the ability to select either rectangle or square shape for the base case model. With regard to the average floor area, the questionnaire results show that the average floor area that is commonly used for office buildings ranges from 300 $m^2$ to 800 $m^2$. Most of the (A/E CO) (63%) have indicated that they generally use packaged HVAC System in their design while the others select Variable Air-Volume HVAC System.

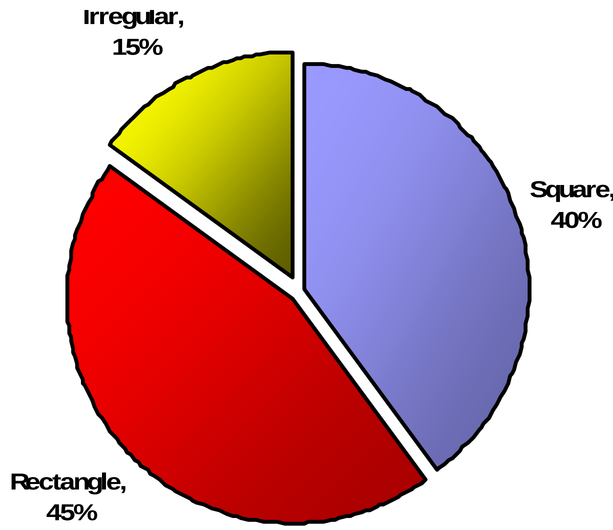



**Figure 3.2** Common geometrical shapes for an office building

### 3.2.3.3 Building Envelope Design Elements

The survey results demonstrated that the most common wall system types for office buildings are, in descending order, the sandwich panel (60%), single leaf (25%), and double leaf (15%). Concerning the exterior wall building material, the majority of the selected designers (75%) use pre-cast concrete as the exterior wall material, whereas only 25% use concrete masonry units (CMU). The results show that 50% of the selected designers generally use curtain walls and pre-cast concrete panel (50%) as exterior wall finishes.

The designers were asked about the roof system that is commonly used, and the results showed that the reinforced concrete slabs were the most widely used roof system (50%). On the other hand, the remaining generally use pre-cast hollow core concrete blanks (25%) and hordi block slabs (25%).

When the designers were asked if they consider including thermal insulation in the wall and roof system, the majority of designers (91%) responded that they include thermal insulation in their design. Extruded polystyrene is commonly used as the thermal insulation material (68%), rock wool (25%), and polyurethane (13%).

#### 3.2.3.4 Window System Design

One of the most important parameters of window design is the type of glazing. The survey results show that double glazing, clear or tinted, is the most widely used by designers for office buildings. Double glazed Low-e is the second glazing type that is normally used, as shown in **Figure 3.3**. The remaining designers have selected different glazing types based on their practice, such as single glazed, single glazed tinted and triple glazed low-e.

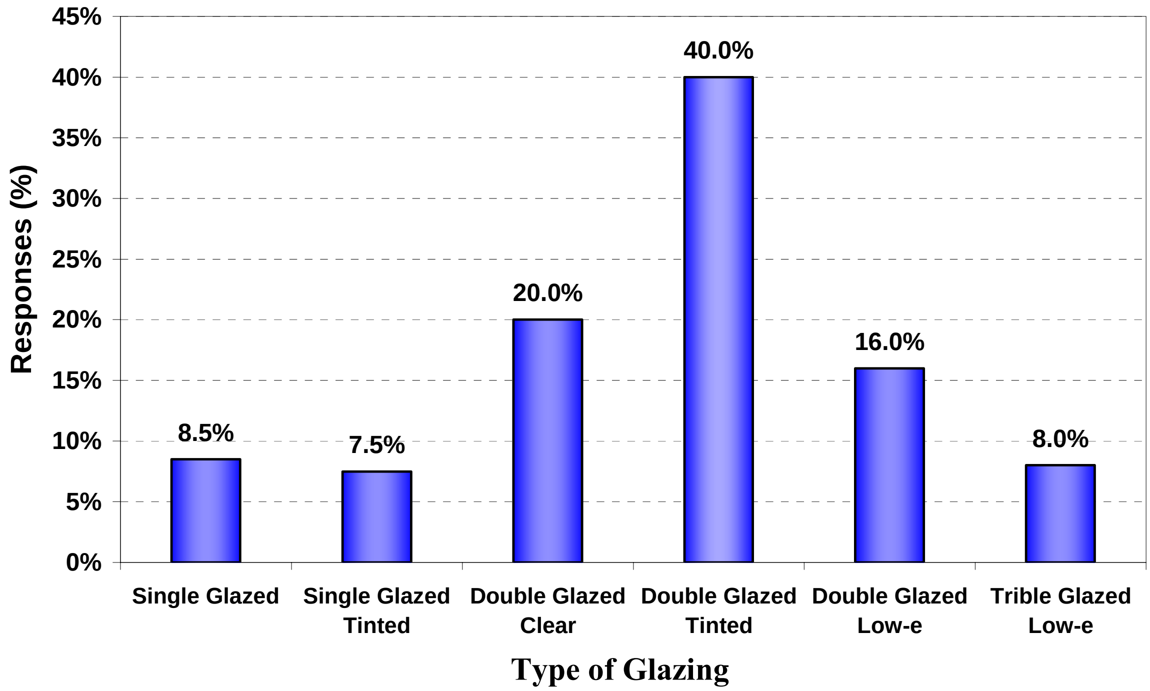



**Figure 3.3** The common glazing types used in office building design

The average (WWR) differs according to façade orientation. For example, the results showed that the average WWR for the north façade is 40% with minimum WWR 25% and maximum WWR 80%. **Figure 3.4** illustrates the WWR results for the other principal orientations. For example, for the east orientation the average WWR is 20%, and for the south façade the average WWR is 25%.

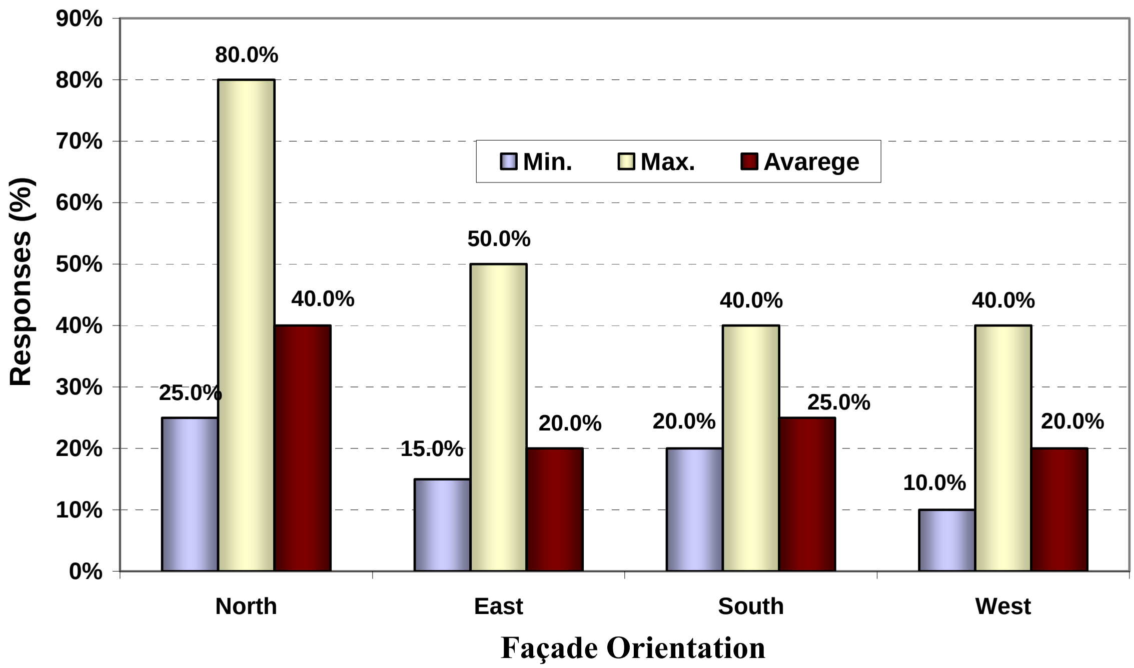



**Figure 3.4** The average window to wall ratio for the main orientations

### 3.2.3.5 Lighting Design Requirements

The designers were asked about the main lighting design requirements that are usually applied for office buildings, such as the illumination level, lighting source type, and lighting power density.

With regard to the required illumination level, the majority of the selected designers (60%) use 500 lux, which is in agreement with the recommended value obtained from lighting standards (IESNA). Alternatively, only 12% use 1000 lux and 13% use 300 lux. The remaining portion of the designers (15%) did not define the required illumination level, which shows the lack of importance that these designers give to the lighting design.

A large proportion of the respondents (42%) did not specify the recommended lighting power density (LPD). The recommended LPD according to the remaining respondents varies greatly from 60 $W/m^2$ to 20 $W/m^2$. It can be concluded that the recommended LPD can not be considered in the base case model, as the survey results did not show acceptable consistency and close results. Recommended LPD can be obtained from available standards and research papers. All the designers indicated that fluorescent lamps are the normally specified lighting sources in office buildings.

Although the results showed that most of the selected designers (88%) consider the utilization of natural lighting in office buildings design, no scientific method or tool is utilized for integration of natural lighting in their design. The responses showed that they consider the utilization of daylighting for different purposes. Although 50% of the designers make use of daylighting for energy conservation, enhancing the visual environment is the main purpose for 30% of the designers. The purpose for the remaining 20% is to provide view to outside.

Experience from previous work is the main source of knowledge for 50% of the designers for daylighting design and prediction. On the other hand, only 25% use manual calculation methods, and 13% do not use any tool for daylight prediction, which proves that the majority of the designers do not utilize available tools for daylight design and rely on their previous experience only.

When the designers were asked whether the utilization of lighting control strategies are recommended, most of them agreed on the importance of using lighting control strategies in order to save lighting energy. **Figure 3.5** shows that the majority recommended dimming and partially On/Off as lighting control strategies. While 22% of the respondents recommended On/Off strategy, the remaining did not recommend any lighting control strategy.

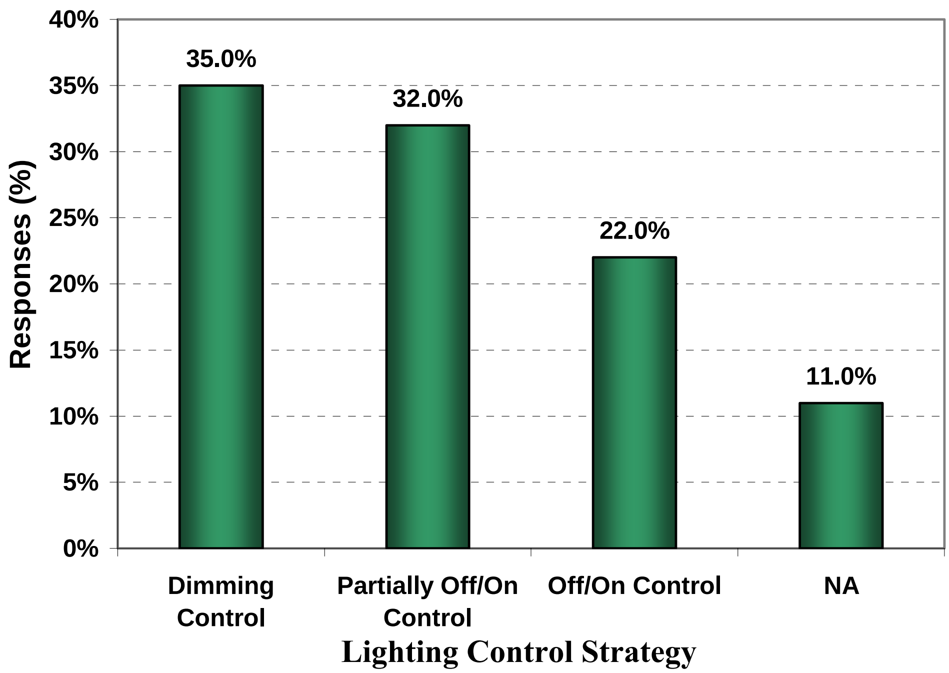



**Figure 3.5** Recommended lighting control strategies

### 3.3 Office building base case development

The main objective of this base case simulation is to investigate the building energy performance and also to find the impact of daylight integration on building energy performance and cooling load. Meanwhile, the office building base case represents a baseline for the parametric analysis which will be conducted to investigate the impact of different window design parameters on building energy performance. To achieve this, a simulation tool, i.e. VisualDOE, is required in order to model a base case for building characteristics and performance.

The base case model necessitates the development of a simulation model that would result in energy performance that has an energy consumption pattern and magnitude similar to the common energy performance obtained from the literature.

The model was developed from the data accumulated from the conducted survey questionnaire. Because detailed building surveys are commonly limited, and available data are regularly incompatible or incomplete for the simulation requirements, the necessary assumptions were based on standards, previous research, and logical judgment to determine the necessary inputs needed by the base case model.

#### 3.3.1 Office building base case characteristics

According to the survey results, a square building with four perimeter zones and an internal zone was selected. The plan and its dimensions of the building base case model are illustrated in **Figure 3.6.**

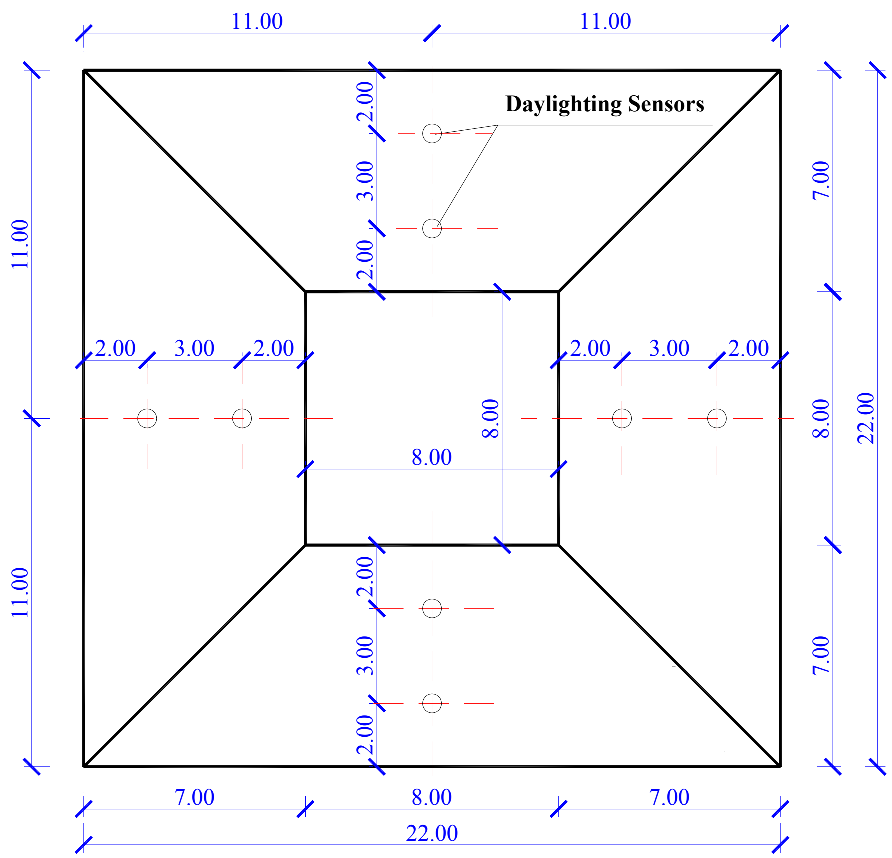



**Figure 3.6** Office building base case plan

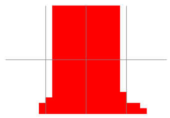
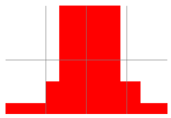
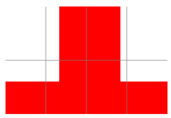
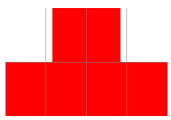
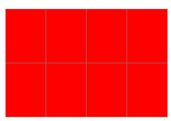
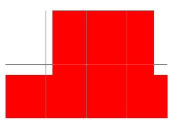
The building covers 484 m$^2$ with 22 m long on each principal orientation. The perimeter zones depth was selected to be 7m according to a research study that stated that daylighting within a building will be significant within about twice the room height of a windowed façade **(Reinhart, 2005)**. Two lighting sensors were located; the first one controls 50% of the lighting at 2.0 m away from the window wall, and the second one controls 30% of the lighting at 5.0 m away from the window wall. Construction of the exterior wall system and roof system was based on the survey results, and the U-values for the constructed wall and roof systems were obtained from VisualDOE. The main base case characteristics are described in **Table 3.1.**

**Table 3.1** Office building base case main characteristics

| Office Building | Description |
|---|---|
| Location | Dhahran(Lat.26° 17' N, Long. 50° 09'E, Altitude 17m) |
| Plan Shape | Square |
| Number of floors | 10 |
| Clear Floor Height | 3.6 m |
| Floor Dimension | 22 x 22 m |
| Gross Floor Area | 484 $m^2$ |
| Zoning | Five Zones, Four perimeter zones and an interior zone |
| Perimeter Depth | 7 m (Reinhart, 2005) |
| Exterior Walls U-Value | 0.53 $W/m^2.^0C$ |
| Roof U-Value | 0.61 $W/m^2.^0C$ |
| Interior Floor U-Value | 0.94 $W/m^2.^0C$ |
| Ground Floor U-Value | 0.51 $W/m^2.^0C$ |
| Solar Absorbance | 0.5 for external walls and 0.5 for the roof |
| Occupancy Density | 15 $m^2$/person (Neufert, 2002) |
| Lighting (LPD) | 22 $W/m^2$ [(Ghisi, 2002) & (Al-Homoud, 1997)] |
| Equipment (EPD) | 15 $W/m^2$ (CIBSE, 1998) |
| Infiltration | 0.5 ACH (Average tightness constructed building) |

Operation schedules have a major impact on the energy performance of any building, and must be designed wisely. Operation schedules were based on logical judgment and common practice. For example, the building is assumed to be 100% occupied during working hours, 20% occupied one hour before and after work, and only 10% during non-working hours, weekends and holidays accounting for personnel working overtime, and those who are present continuously like security and maintenance staff. The lighting system is assumed to be 100% On during occupied periods and only 10% On during unoccupied periods, weekends and holidays. **Table 3.2** illustrates the complete operation schedules which were used in the office building base case.

**Table 3.2** Office building base case operation schedules

| Schedule | | Schedule Description |
|---|---|---|
| Occupancy |  | 100% during occupied periods, 20% one hour before and after work |
| Lighting |  | 100 % during occupied periods and 10% for unoccupied periods, weekends and holidays |
| Equipment |  | 100% occupied periods, 30% during unoccupied periods, weekends and holidays |
| Infiltration |  | 100% occupied periods, 50% during unoccupied periods, weekends and holidays |
| Fan Profile |  | 100% all the time |
| Outside Air |  | 100% for occupied periods and 40% during unoccupied periods, weekends and holidays. |

The HVAC system is an essential system and has a major role in the building energy performance. According to the survey questionnaire results, a packaged system is selected for the base case model zones. The main system characteristics of HVAC system used are described in **Table 3.3,** including the type of the system, cooling and heating temperature, and ventilation rate. The weather file for Dhahran 2002 was selected to be used in the energy simulation process.

**Table 3.3** HVAC System characteristics

| Characteristics | Description |
|---|---|
| System Type | One System For each Zone (Packaged system) |
| Cooling Design Temp. | 24 °C |
| Heating Design Temp. | 21 °C |
| Ventilation | 10 l/s (ASHRAE 62, 1999) |
| Weather file | Dhahran 2002 |

For the purpose of daylight integration, lighting control properties have to be defined. A dimming control was selected in accordance with the survey results, and this strategy provides the flexibility for the response to every change in the natural lighting. **Table 3.4** illustrates the main properties of the lighting control which will be utilized in the simulation process.

**Table 3.4** Lighting control properties

| Characteristics | Description |
|---|---|
| Daylight Control | Dimming Control |
| Illuminance | 500 lm/$m^2$ (lux) (IESNA, 2000) |
| Daylight Control Sensors | Two Sensors (one controls 50% of the lighting 2 m away from the window wall, and the second controls 30% of the lighting 5 m away). |

With respect to the window design, the survey results help to define each element. The window-to-wall ratio (WWR) was defined for the four main orientations as follows: north (40%), east (15%), south (25%), and west (20%). Based on the questionnaire results, double clear glass was selected as the glazing type, and the tinted glass was excluded because it provides less natural lighting than the clear glass. Based on logical judgment and common practice, the window sill was defined as 1m high and the window height is 1.20 m representing a starting height, and the other alternative heights will be investigated later in section 4.4.

## 3.4 Initial Verification of Simulated Results

Following the formulation of the base case and initial verification of input data, the base case model was run through the VisualDOE program. Simulation results, including energy performance, building lighting energy consumption, and building peak cooling load, were analyzed for comparison with available data for similar buildings from the literature. A sample of VisualDOE input and output files can be found in **Appendix B.**

### 3.4.1 Building Energy Performance

The energy performance of the base case provides an indication that the model is working properly. The simulation results showed that the total energy consumption for the building base case is about 1,434 MWH per year. Energy consumption for cooling represents the major part of about 53% of the total energy consumed. However, the lighting takes about 23%, and the energy consumed by the equipments is about 24% **(Figure 3.6).** These results are reasonable if compared to the energy consumption of office buildings in local area and other places around the world. **Table 3.5** provides a comparison of the energy performance of the base case with other results obtained from other research studies.

**Table 3.5** Energy consumption end-use comparisons

| location | Energy End-Use (%) | | | Ref. |
|---|---|---|---|---|
| | Cooling | Lighting | Others | |
| ASEAN Cont. | 61.1% | 22.5% | 15.5% | Ghisi, 2002 |
| USA | 30% | 35% | 35% | Ghisi, 2002 |
| Hong Kong | NA | 20-30% | NA | Lam, 1998 |
| Egypt | NA | 36% | NA | Abdl-Mohaimen, 2005 |
| Saudi Arabia | 60% | 20% | 20% | Hasnain, 2000 |
| Base Case | 53% | 23% | 24% | Simulated |

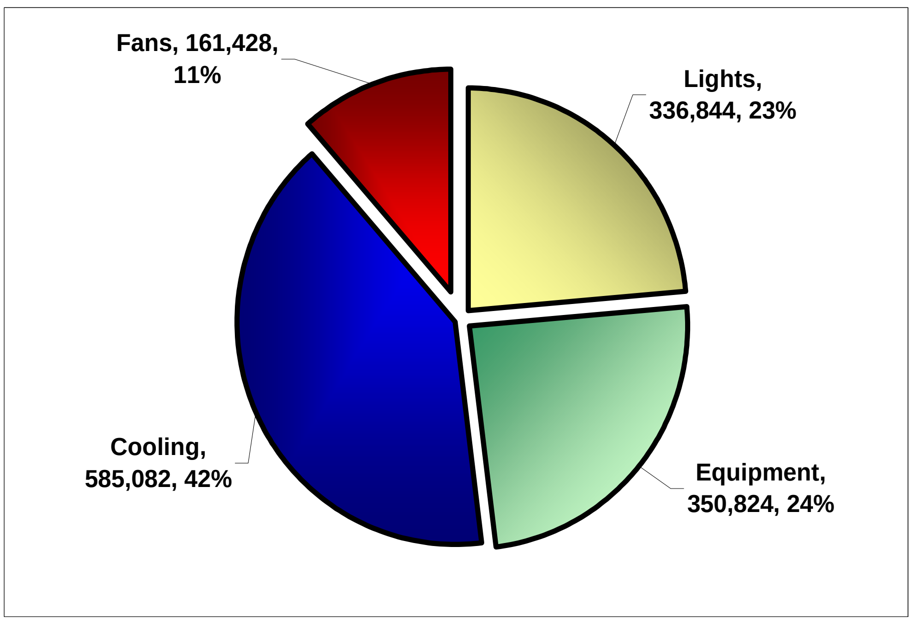



**Figure 3.7** Energy consumption of the base case

The results of the monthly energy consumption, as illustrated in **Figure 3.8**, show that there is a logical performance, as the energy consumption increases during the summer months because of higher cooling load requirements. On the other hand, the energy consumption decreases during the winter months, as the demand for cooling is reduced by the change in outside weather conditions.

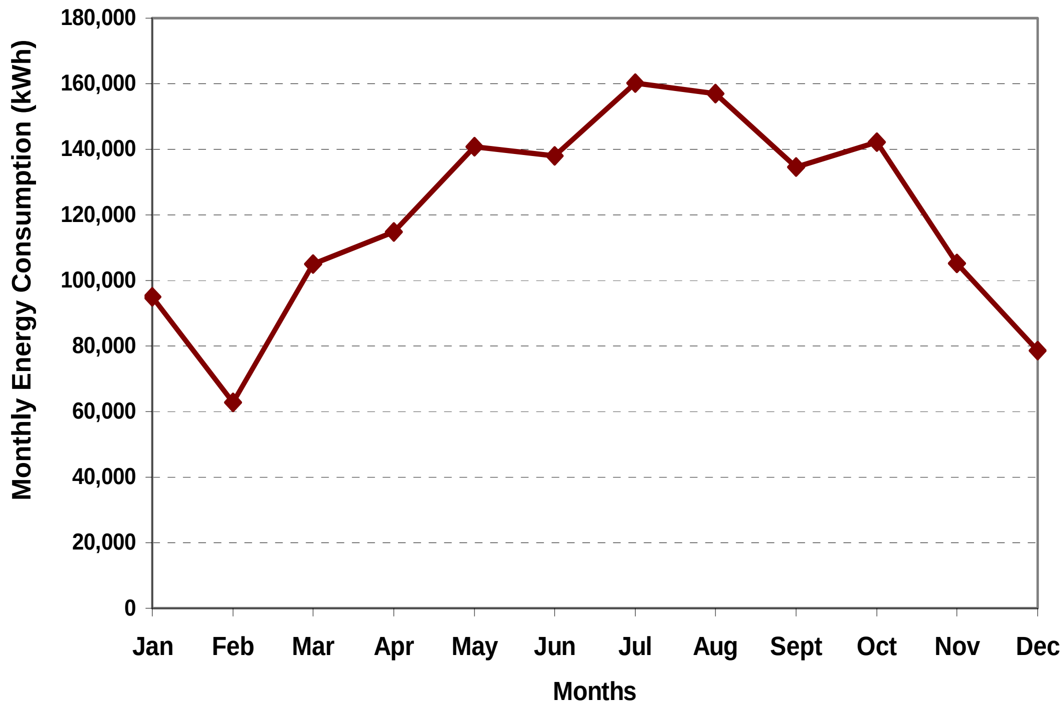



**Figure 3.8** Monthly energy consumption for the base case model

### 3.4.2 Daylight Illumination Level Investigation

The illumination level for the four perimeter zones was determined for two reference points to investigate the possibility of integrating the use of daylighting with the artificial lighting. The results showed a great potential for the integration of natural lighting, as the average of calculated illumination level exceeded the required illumination level (500 lux) during most of the year. For the purpose of illustration, it was found that the average illumination level in the north zone is greater than 500 lux for most months in the first reference point, and it is nearly approaching the required illumination level for the second point, as shown in **Figure 3.9.a.** The results also showed an increase in the illumination level during the summer months, perhaps because of the long daytime or because the sun path is higher at this time of the year.

For the south zone, it is observed that the illumination level was greater than the required value for most of the year. This provides great potential for the utilization of natural lighting. It can be seen from **Figure 3.9.c** that the illumination level is lower in summer (May, June, July and August) than in winter. This is because the sun's altitude is low during these months, facilitating the penetration of direct sunlight into the built space. The resulting illumination levels for the west and east zones also indicated great potentials for daylight integration with artificial lighting, as shown in **Figure 3.9.b** and **Figure 3.9.d.**

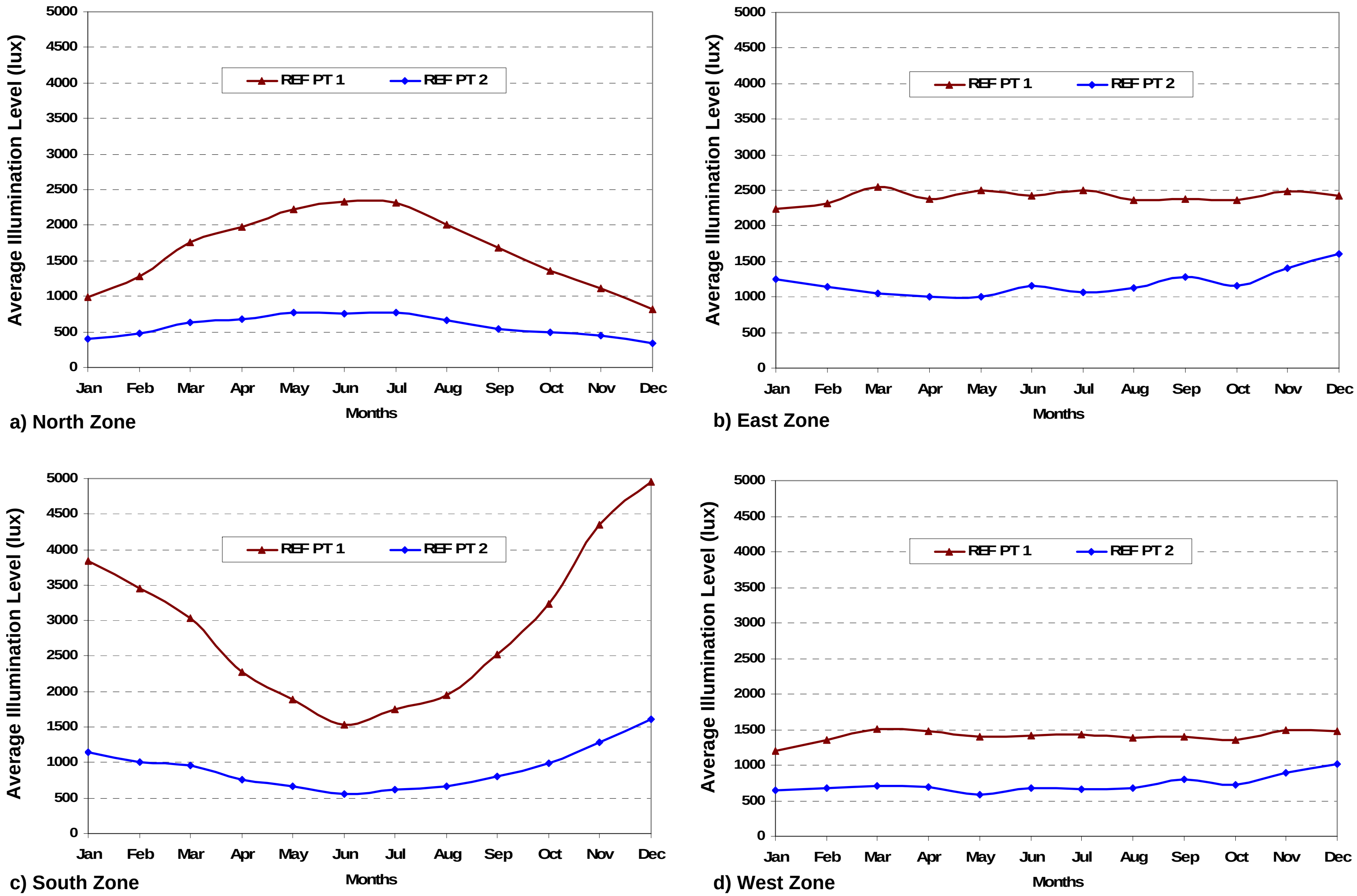



**Figure 3.9** Monthly average illumination level for [a) North zone, b) East zone, c) South zone, and d) West zone]

# CHAPTER FOUR

# IMPACT OF DAYLIGHT INTEGRATION WITH ARTIFICIAL LIGHTING: PARAMETRIC ANALYSIS

## 4.1 Introduction

Daylight, if properly utilized, is regarded as the finest source of light because of its quality spectral composition as well as its potential to reduce energy consumption. Reviewed studies have demonstrated that daylight integration with artificial lighting can significantly reduce both lighting energy consumption and total building energy consumption. In addition, it can decrease the building cooling load which leads to a smaller air-conditioning system **(Li, 2001)**.

A base case model was formulated in order to investigate the impact of daylight integration with artificial lighting on building energy performance. This investigation was performed to find the impact of daylight integration on both building energy consumption and building cooling load. This investigation was conducted once the base case model was verified for accuracy and logical results for energy consumption. In this chapter, the impact of various window design parameters, such as window area, window height, and type glazing, is studied to determine the influence of these on both lighting energy consumption and total building energy consumption. The expected energy saving as a result of daylight integration with artificial lighting is also investigated for different window design parameters.

Results from the parametric analysis has provided a strong case for the development of a design tool that provides assistance for the designers on the selection of a window that provides the sufficient natural lighting with the consideration of energy efficiency.

## 4.2 Simulation Results of Daylight Integration with Artificial Lighting

A reduction in lighting energy consumption and total energy consumption can be achieved when daylighting is integrated with artificial lighting. In addition, a reduction in the building cooling load can be obtained, which leads to a smaller HVAC system and a reduced cooling energy consumption. Simulation of base case model when daylighting is integrated with artificial lighting was carried out, and the results were analyzed. The results include the energy consumption of the building, building lighting energy consumption, and the peak cooling load. The impact of the integration of natural lighting with the artificial lighting on both energy consumption and peak cooling load was investigated, and the results are shown in the following sections.

### 4.2.1 Building Energy Consumption

There are three main components for the building energy consumption. These are: cooling energy consumption, lighting energy consumption, and equipment energy consumption. The integration of daylighting with artificial lighting has an effect on both the lighting and cooling energy consumption. In the present study, the daylight is integrated by using a dimming control strategy with two lighting sensors in order to maintain the required illumination level. A comparison between the energy consumption of the office building base case model, with and without daylighting integration, is shown in **Table 4.1.** It is clear that energy reduction is achieved for all energy consumption components. **Figure 4.1** graphically shows the relative impact of daylighting integration on energy consumption reduction on various components. It can be seen that the bulk of energy reduction is obtained through lighting energy with about 35%. This indicates the high potential of daylighting to compensate for artificial lighting. In addition, the simulation results have proved that the utilization of natural lighting has an influence on the cooling energy, which is decreased by 9%. The reduction in cooling energy is a result of the reduction in the heat gain from the artificial lighting and, consequently, the associated cooling load. The daylight integration has resulted on a total reduction of about 13% from the total building energy consumption, which can be regarded as a reasonable reduction and can be directly reflected in the energy cost.

**Table 4.1** Energy consumption of the base case model (kWh)

| **Alternative** | **Lighting Energy** | **Equipment Energy** | **Cooling Energy** | **Total Energy** |
|---|---|---|---|---|
| Base Case | 336,844 | 350,824 | 746510 | 1,434,178 |
| Base Case with Daylight Integration | 220,215 | 350,824 | 680306 | 1,251,345 |
| Energy savings (%) | 34.6% | 0.0% | 8.9% | 12.7% |

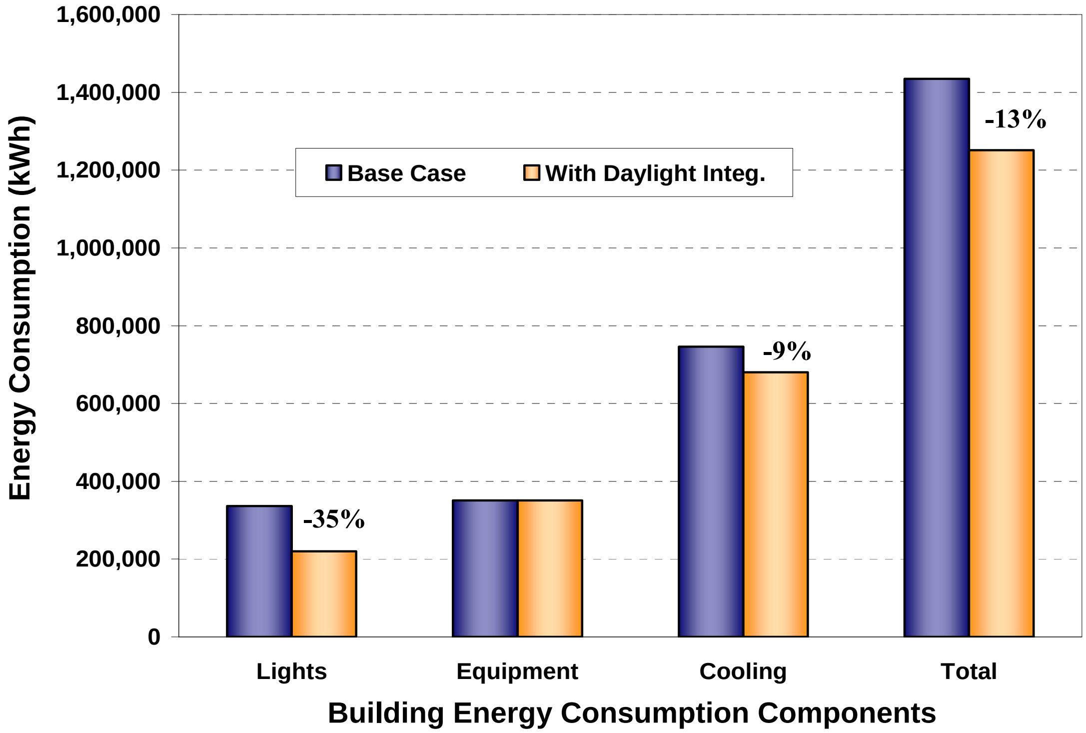



**Figure 4.1** Impact of daylight integration on the building energy consumption

### 4.2.2 Building Peak Cooling Load

One of the advantages of the daylight integration is minimizing the cooling load, which leads to a smaller HVAC system. **Figure 4.2** compares the peak cooling load of the building when daylight is and is not integrated with artificial lighting. The results demonstrate that the integration of natural lighting has reduced the peak cooling load for the whole building by approximately 11%. Additionally, results shown in **Figure 4.2** indicate that a different reduction in the cooling load is obtained in the perimeter zones. For example, in the north zone it is about 10% and in the east zone 13%. Only about 6 %

reduction in peak cooling load is obtained in the west zone and 8% in the south zone. This can be attributed to the different levels of exposure to solar radiation, which influences both the heat gain and the amount of available natural light.

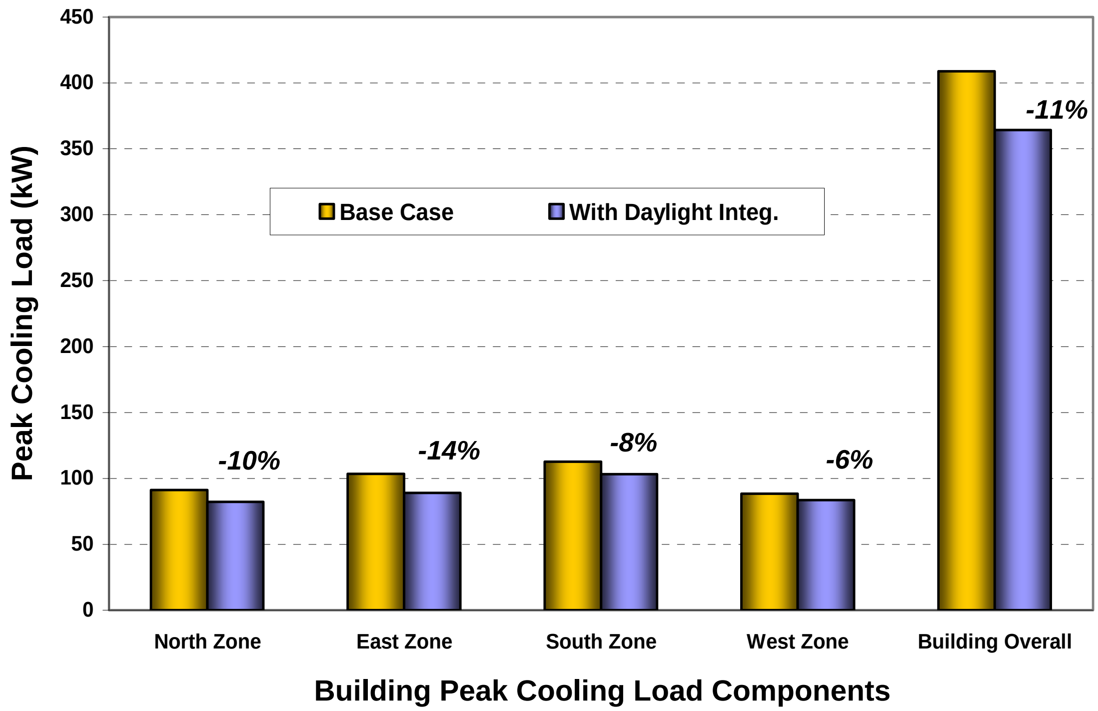



**Figure 4.2** Impact of daylight integration on building peak cooling load

## 4.3 The Impact of Various Glazing Types on Energy Performance

The glazing type and the number of glazing layers are among the critical parameters the designer must consider when designing windows. They can affect both the amount of light transmitted into the built space and the magnitude of solar heat gain, which in turn results in an increase in the cooling load.

Many types of glazing with different thermal and physical characteristics are available for designers to choose from. Four different glazing types have been investigated in this study, based on the commonly used types in the local area. The tinted glass is not selected in this study, because its low lighting transmittance reduces the amount of daylighting entering the built space. Thermal and lighting characteristics of the four glazing types are shown in **Table 4.2**, including the number of panes, the visible transmittance, and the shading coefficient (SC).

**Table 4.2** Glazing types used in the parametric analysis

| Glazing Type | No: of panes | Visible Transmittance | Shading Coefficient (SC) | Solar Heat Gain Coefficient (SHGC) | U-Value $W/m^2.K$ |
|---|---|---|---|---|---|
| Single-glazed clear 6 mm **(Clr SG)** | 1 | 0.88 | 0.95 | 0.81 | 6.17 |
| Double-glazed clear 6/12/6 mm **(Clr DG)** | 2 | 0.78 | 0.81 | 0.70 | 2.74 |
| Double-glazed clear low-e 6/12/6 mm **(DG Low-e)** | 2 | 0.74 | 0.65 | 0.56 | 1.78 |
| Double-glazed clear heat-mirror 6/12/6 mm **(DG HM)** | 2 | 0.53 | 0.40 | 0.34 | 2.02 |

### 4.3.1 Lighting Energy Consumption

The study investigated the impact of different glazing types on the lighting energy consumption when daylight is integrated with the artificial lighting. The analysis was performed for 1.90 m window height, different WWRs, and principal zone orientations. The simulation results showed that, for all possible WWRs and all glazing types, the lighting energy consumption is significantly reduced when daylight is integrated with the artificial lighting. **Figure 4.3.a** shows that the lighting energy consumption was dramatically reduced when the window area was increased from 0% to 5%, and it steadily decreased as the WWR increased up to 50% in the north zone.

The potential reduction in lighting energy consumption ranges from almost 40% to approximately 54% for all glazing types, as shown in **Figure 4.3.a.** The results have demonstrated that the higher the visible transmittance of the glazing type, the lower the lighting energy consumption. This is because the amount of lighting transmitted into the built space is higher, which will, in turn, reduce the artificial lighting usage. It can be observed that, when the WWR is increased, the lighting energy consumption is decreased for all glazing types, and this is because of the increase in the transmitted light into the space. The difference in lighting energy consumption between the types of glazing used in this analysis decreases at a higher WWR, and this difference becomes negligible for high WWRs. Similar lighting energy consumption is obtained for the other zone orientations, as indicated by the simulation results shown in **Figure 4.3.** Lighting energy consumption for the remaining window heights can be found in **Appendix C**.

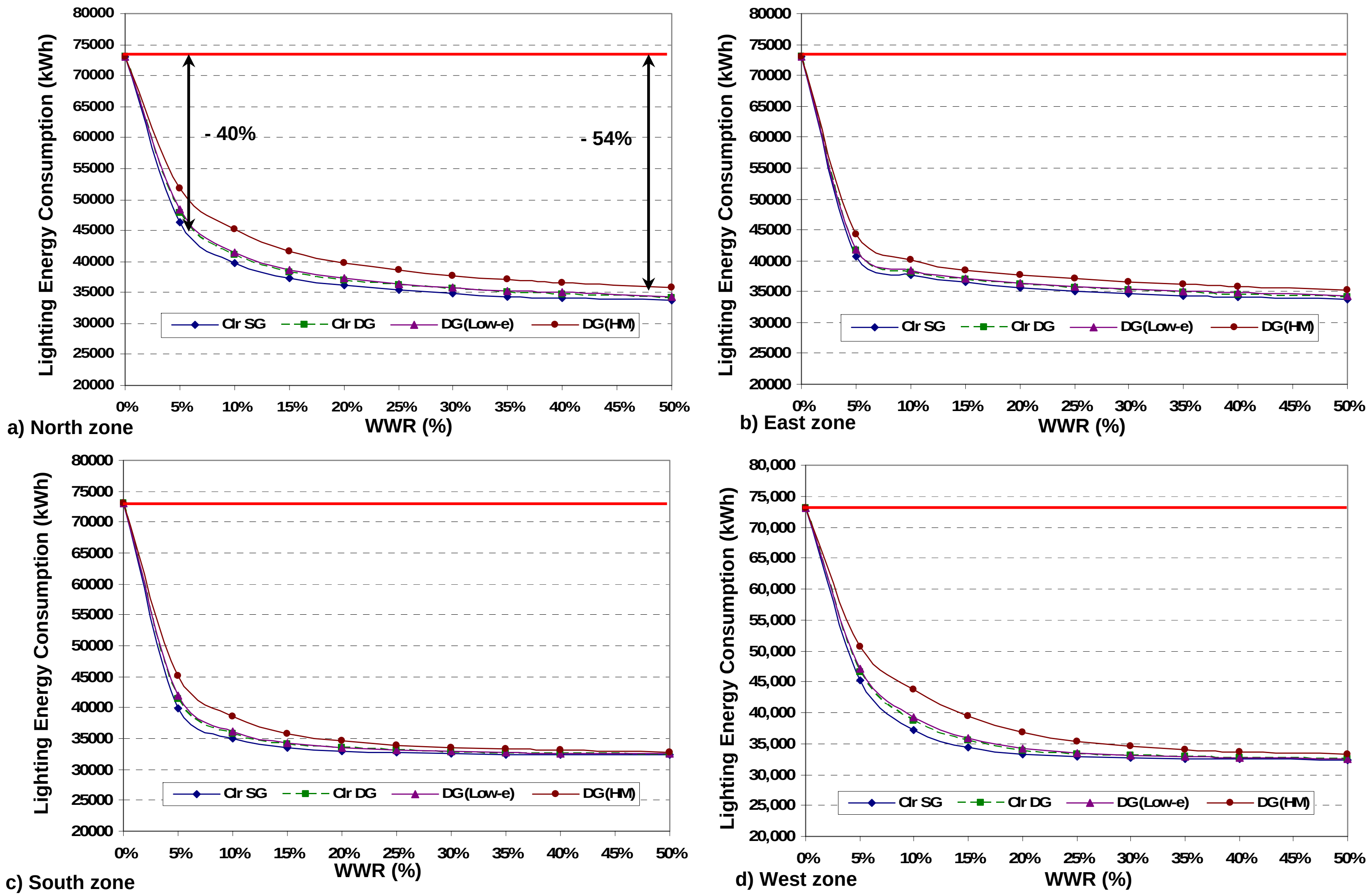



**Figure 4.3** Lighting energy consumption for various glazing types – 1.90m window height – [a) North zone, b) East zone, c) South zone, and d) West zone]

### 4.3.2 Total Building Energy Consumption

The selection of windows glazing type is a critical design decision. It will have a major impact on any building's energy consumption. The impact of different glazing types on the total energy consumption was investigated as a part of this study. The study was carried out for the selected glazing types mentioned previously and for 1.90 m window height.

It can be concluded from the results that the shading coefficient value for a specific glazing type is the main factor that determines the energy performance of a particular window. The results have shown that the lower the shading coefficient value, the lower the energy consumption. This is shown in **Figure 4.4.a.**

**Figure 4.4.a** shows that the integration of natural lighting apparently reduces the amount of total energy consumption for all glazing types. It can be observed that there is a tangible reduction in the energy consumption, varying in magnitude according to the glazing type and window area. For small window areas, there is almost no difference in the amount of reduced energy consumption for all glazing types when daylight is integrated. On the other hand, a noticeable difference in energy consumption is obtained as the window area is increased. When double-glazed heat-mirror glass is used, the resulting energy consumption is slightly greater than other glazing types in small window areas (5-15%) provided that there is an integration of daylighting. However, this glazing type results in lower energy consumption than other glazing types at higher WWR.

There is a similar trend in energy consumption for the other zone orientations, but the amount of energy consumption varies from one zone orientation to another as shown in **Figure 4.4**. It can be observed that total energy consumption is higher in the east, west and south zones than in the north zone. A slight difference is observed in the total energy consumption when the glazing type is changed in the north zone. However, this variation is higher in the other zones.

It can be noticed that the reduction in energy consumption is higher when double-glazed heat-mirror glass is used in the east and south zones, but lower in the other zone orientations as shown in **Figure 4.4.b and Figure 4.4.c**. This can be attributed to the long exposure to direct solar radiation during the day time, and one of the properties of this glazing type is that it prevents most of the direct solar heat gain. In addition, the use of double-glazed heat-mirror glass provides the lowest energy consumption for all principal zone orientations especially at large WWR. Energy consumption for the remaining window heights and principal zone orientations can be found in **Appendix D**.

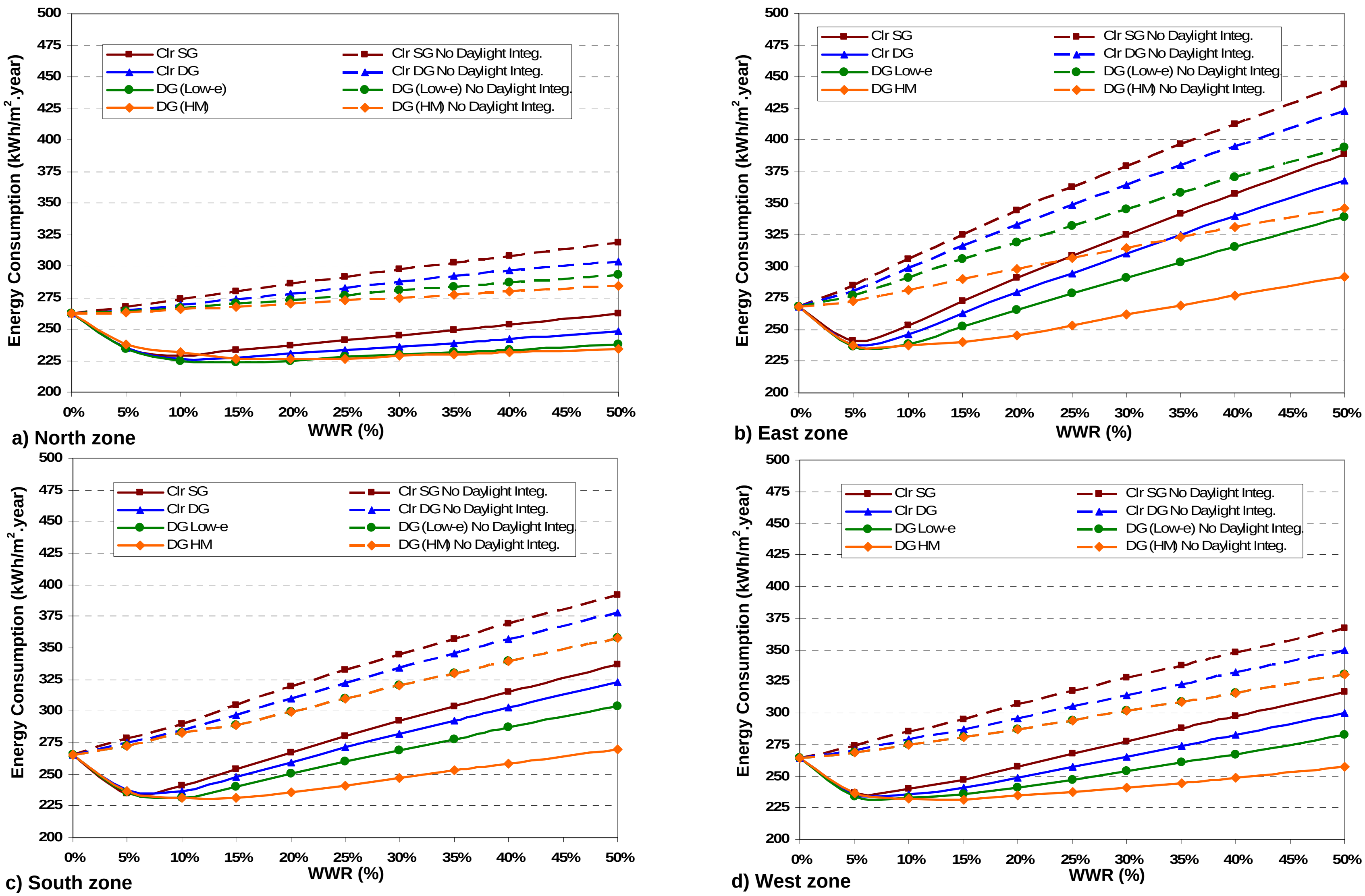



**Figure 4.4** Impact of daylighting integration on total energy consumption for various glazing types – 1.90m window height – [a) North zone, b) East zone, c) South zone, and d) West zone]

### 4.3.3 Potential for Energy Savings

The reduction in energy consumption is one of the main results when daylight is integrated with artificial lighting. The potential for energy savings due to daylight utilization was examined for various glazing types and principal zone orientations. The results proved that the potential energy savings differed according to the glazing type and the zone orientation.

**Figure 4.5.a** shows the expected energy savings for the north zone with 1.90 m window height for various glazing types and different window areas. Results show that there is a potential for energy savings, ranging from 10% to 19% for all glazing types based on the selected WWR. It can be seen that the glazing type with high visible transmittance, i.e. single glazed clear, provides higher energy savings than other glazing types when a small window area is used (5-10%). On the other hand, double glazed clear Low-e provides the highest energy savings of 17% to 19% when larger window areas (20-50%) are used. This is because the single glazed clear provides more natural light than other glazing types when small window areas are used, whereas with larger window areas there is an increase in heat gain along with the admitted light. At higher window areas, double glazed Low-e is better, as the amount of heat gain through it is smaller because of its thermal characteristics.

**Figure 4.5.b** shows the expected energy savings for the east zone with 1.90 m window height for various glazing types and window areas. The results demonstrate that the expected energy savings vary from 10% to 18% for all glazing types, depending on

the window area used. Because of the high exposure to direct solar radiation in the east zone, the glazing type with low shading coefficient provides high energy savings. It can also be observed that the double-glazed heat-mirror glass provide less energy savings than other glazing types at small window area but higher energy savings at larger areas. This is because this glazing type can block the direct solar heat more than other types and can provide sufficient light into the space at large window areas.

The resulting energy savings for the south zone are illustrated in **Figure 4.5.c.** These results are for 1.90 m WH, various glazing types and WWRs. A reduction in energy consumption of 12% to 18% is achieved for all glazing types and WWRs. The maximum energy savings are achieved with double glazed low-e at small window area (5-15%). On the other hand, when WWR is increased, the maximum energy savings occurred with double-glazed heat-mirror glass. This can be attributed to the reduction in direct solar heat gain when double-glazed heat-mirror glass is used.

Similar results are obtained for the west zone as shown in **Figure 4.5.d.** 11% to 17% of energy savings is achieved for all glazing types and WWRs. It can be noticed that single-glazed clear windows provided higher reduction in energy consumption than other glazing types at small WWR (5%-15%). At larger window areas, double-glazed heat-mirror glass provides the maximum energy savings (16-17%). Energy savings for the remaining window heights and principal zone orientations can be found in **Appendix E**.

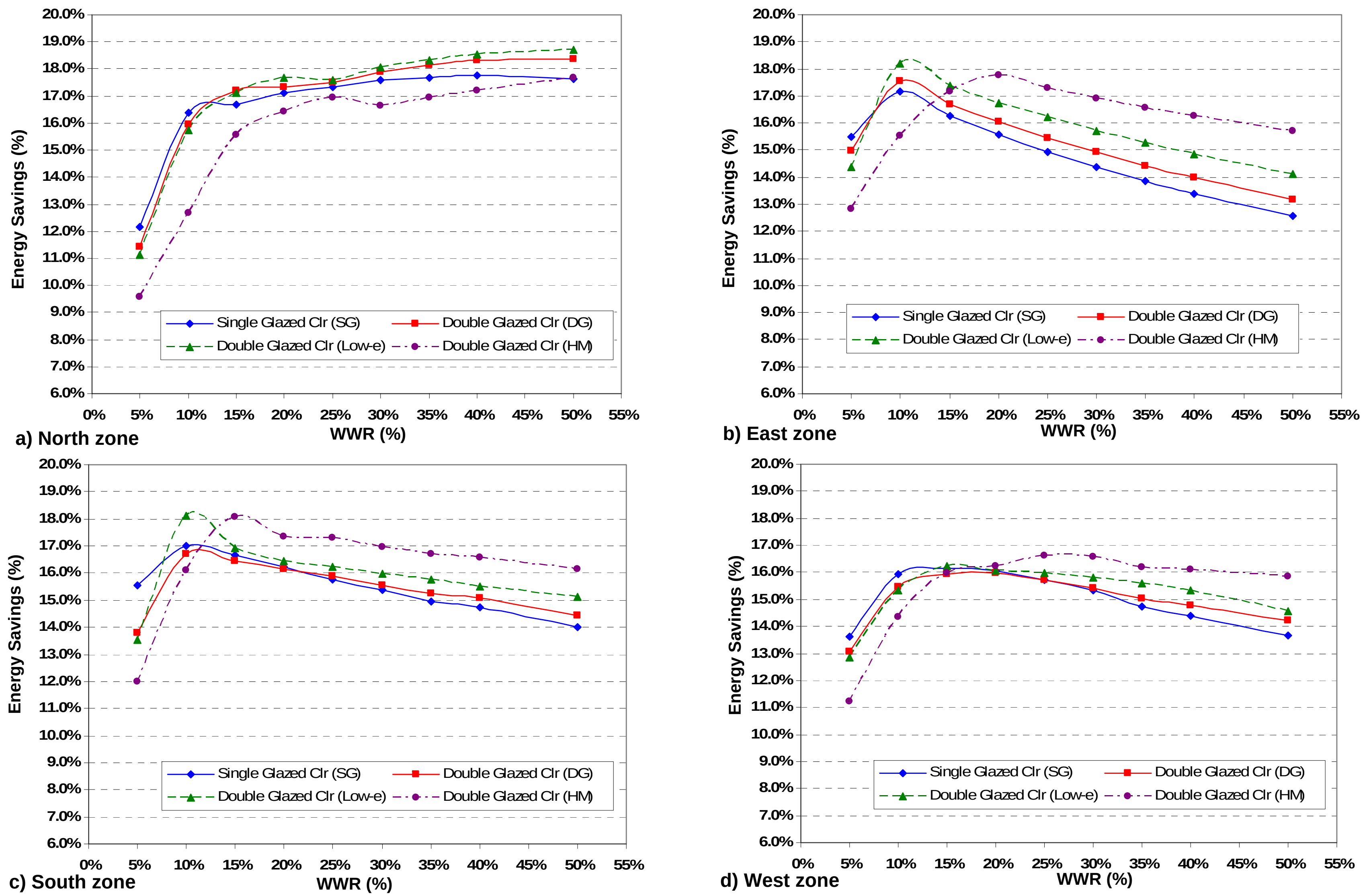



**Figure 4.5** Expected energy savings for various glazing types – 1.90m window height – [a) North zone, b) East zone, c) South zone, and d) West zone]

## 4.4 The Impact of Various Window heights on Energy Performance

Window height is the distance from the window sill to the window lintel. Window height has a major role in determining the amount of natural light transmitted into the built space, as proved by previous studies. The larger the window height, the greater the amount of light transmitted into the space. Window height also has a significant impact on the depth which light can reach in the interior space. The daylight penetration depth increases as the window height is increased.

In this research study, various window heights were addressed starting from 1.20 m up to the ceiling height (2.60 m). Five different window heights were selected with an interval of 0.35 m to cover a wide range of possible window heights, as shown in **Figure 4.9.** Window sill is maintained at 1m for all simulation processes, as the influence of daylight is preferred at the work plane height (0.76 m) and can be ignored at lower height. This investigation was performed for the four principal zone orientations and different glazing types. The results revealed that there is a recognizable influence of window heights on the building energy performance, and these results are explained below.

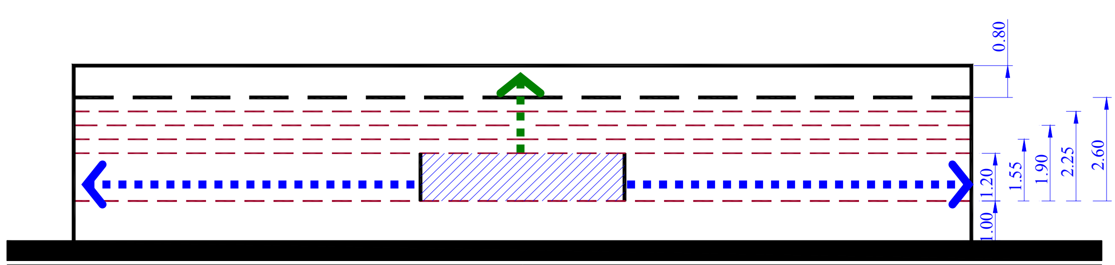



**Figure 4.6** Investigated window configuration schemes

### 4.4.1 Lighting Energy Consumption

The impact of different window heights on the building lighting energy consumption was examined when daylighting and artificial lighting are integrated. The dimming control strategy was utilized in this analysis with two reference points, as mentioned in the base case model characteristics. This analysis was performed only for a double-glazed clear window, but for various WWRs and principal zone orientations.

The results obtained from the simulation process demonstrated that, for all window areas and all window heights, the lighting energy consumption is considerably reduced when daylight is integrated with artificial lighting. While the results show that there is a dramatic reduction in the lighting energy consumption when the WWR is increased from 0% to 10%, the lighting energy consumption gradually decreases when WWR is increased from 10% up to the maximum possible window area, as illustrated in **Figure 4.7.a.**

**Figure 4.7.a** also shows that the potential of minimizing lighting energy consumption ranging from about 41% to almost 53% for all window heights. Specifically, as the window height increases, lighting energy is reduced for the same WWR. This is the result of the increase in the amount of light transmitted into the interior space. There is also an increase in the daylight penetration depth, which lowers the need for artificial lighting in the interior space. It can be observed from **Figure 4.7** that the lighting energy consumption is decreased when the window area is increased for all window heights, and

this can be attributed to the increase in the amount of transmitted light into the built space.

Generally, it can be noticed that the variation in lighting energy consumption for the analyzed window heights is minimized as the WWR is maximized until this variation becomes unnoticeable. Similar lighting energy consumption trends for the other principal zone orientations are shown in **Figure 4.7**, which represents the resulting energy consumption for the principal zone orientations. The lighting energy consumption is reduced by almost the same percentage, i.e. (40-50%) for all zone orientations when daylight is integrated with the artificial lighting.

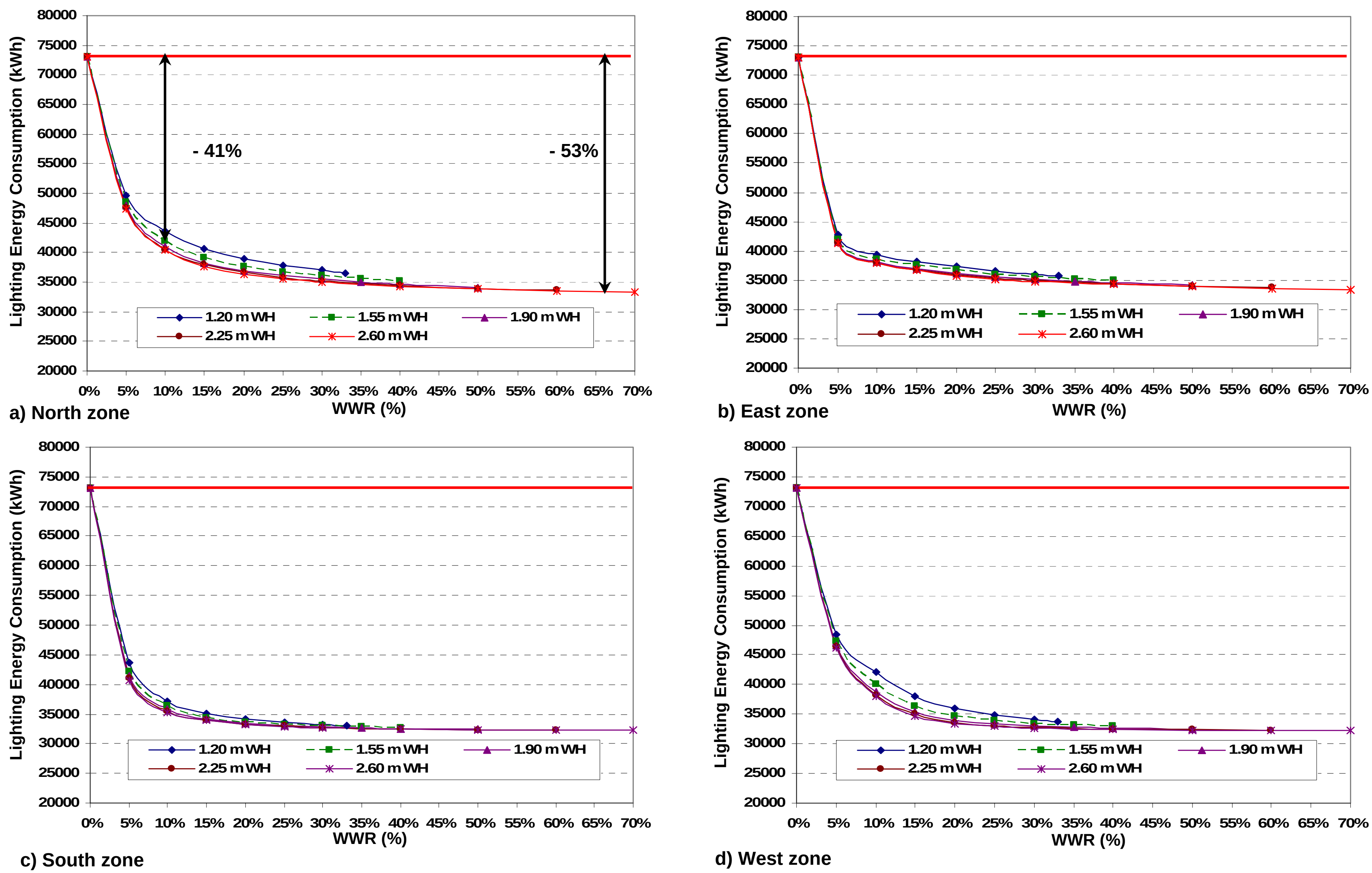



**Figure 4.7** Lighting energy consumption for various window heights – double-glazed clear – [a) North zone, b) East zone, c) South zone, and d) West zone]

### 4.4.2 Total Building Energy Consumption

The determination of window height is an important design decision as it may influence building aesthetics, construction cost, and energy lighting performance. The influence of different window heights on the total building energy consumption was studied for the principal zone orientation when a double-glazed clear window is used.

The simulation results showed that there is only a slight difference in the building's total energy consumption for the different window heights. **Figure 4.11** shows that the larger the window height, the lower the total energy consumption. The reduction in energy consumption can be explained by the reduction in lighting energy, as it exceeds the resulting increase in cooling energy due to the larger window area.

Furthermore, it can be observed from **Figure 4.11** that the total energy consumption is considerably minimized when daylighting is integrated with artificial lighting for all window heights. Resulting graphs indicate that there is almost no difference in total energy consumption for all window heights when daylight is not integrated with artificial lighting. However, a slight difference in total energy consumption is obtained at various window heights when daylighting is integrated with artificial lighting. This difference is small at small window areas (5-15%) and it is minimized as WWR is increased until this variation vanishes for large window areas. A similar trend in total energy consumption is obtained for the remaining principal zone orientations, but with a difference in energy consumption value, as seen in **Figure 4.12**. It can be seen that the total energy consumption is higher in the east zone than in the north zone.

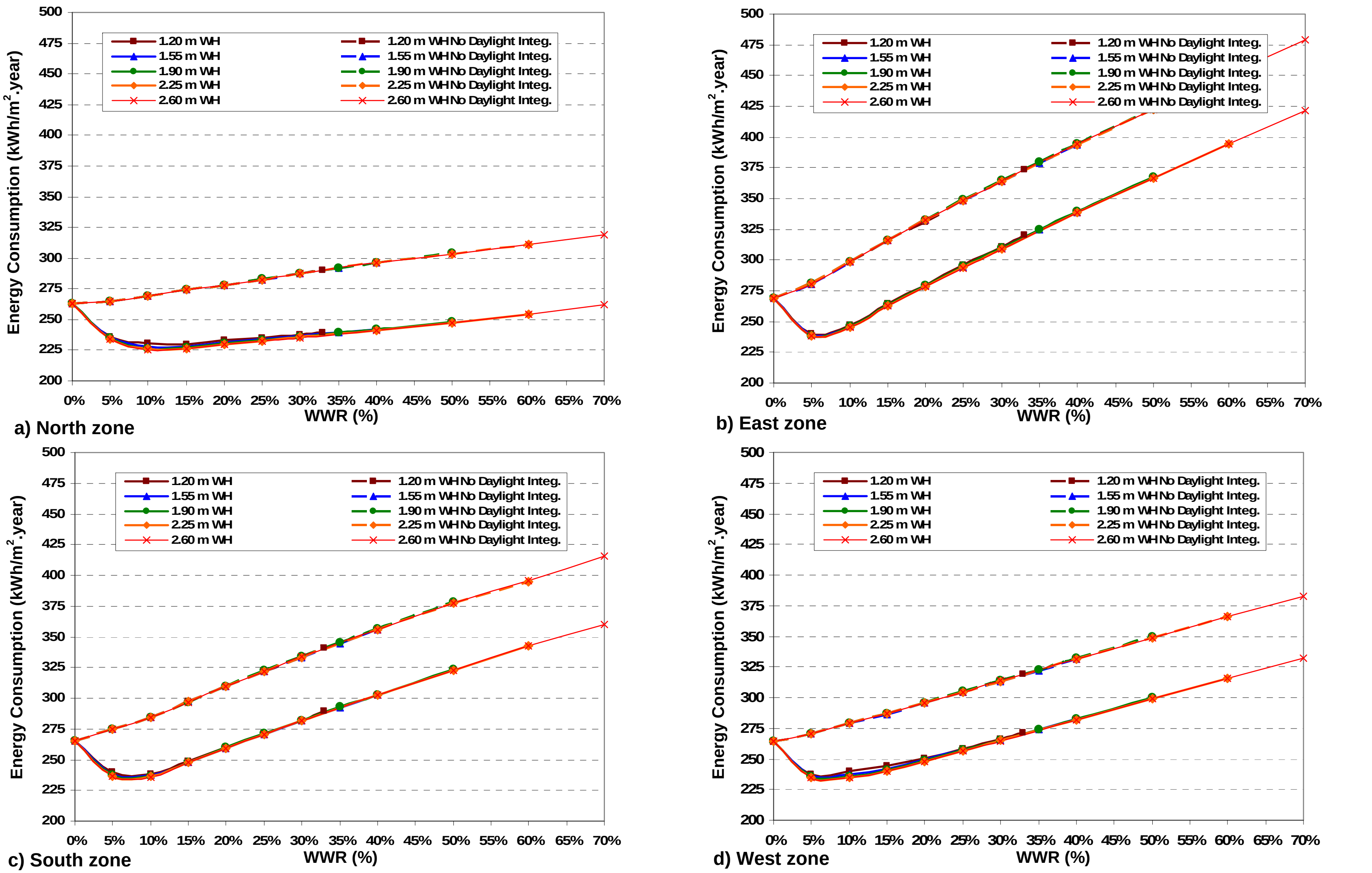



**Figure 4.8** Total energy consumption for various window heights – double-glazed clear – [a) North zone, b) East zone, c) South zone, and d) West zone]

### 4.4.3 Potential for Energy Savings

The integration of daylighting with artificial lighting is a main strategy to achieve energy conservation in buildings. This study has investigated energy savings due to the integration of daylight with artificial lighting for various window heights and principal zone orientations. The initial value for window height was 1.20 m, which was increased until reaching the maximum possible height (2.60 m) with 0.55 m segments.

Results indicated that reduction in energy consumption due to integration between daylighting and artificial lighting varies according to the window height and zone orientations.

**Figure 4.9.a** shows the possible energy savings for various window heights, north zone, double glazed clear glass, and different WWRs. The results demonstrated that the potential of energy savings is increased as the window height is maximized for all window areas. This is obviously due to the increase in the amount of natural lighting transmitted into the built space due to the increase in the lighting penetration depth. It was observed from the energy saving results that there is a clear difference in energy savings when the window height is increased from 1.20 m to 1.55 m, but this difference decreases as window height is increased from 1.55 m to 2.60 m.

Energy savings due to daylighting integration can be considerably increased by increasing WWR. Increasing the WWR from 5% to 15% resulted in an increase of up to 6.5% in energy savings. On the other hand, there is no significant change in energy savings for larger WWRs up to 50%. Beyond the 50% WWRs, the net energy savings start to decrease gradually.

**Figure 4.9.c** shows the possible energy savings for various window heights, south zone, clear double-glazed window, and different WWRs. It can be noticed that similar results are obtained. The larger the window height, the greater the expected energy savings, as there is an increase in the transmitted light into the interior space through higher windows. However, there is only a slight difference in energy savings for the various window heights used. Additionally, a significant increase in energy savings is obtained when the WWR is increased from 5% to 15%, whereas the potential for energy savings is continuously decreased with larger WWRs up to 70%. This can be attributed to the impact of direct solar heat gain on the cooling energy, which is expected to have a greater impact than the reduction in lighting energy resulting from lighting integration. Results for the other zone orientations, i.e. east and west, have a profile similar to the north and south zones, but they differ slightly in the magnitude of energy savings, as can be seen in **Figure 4.9**.

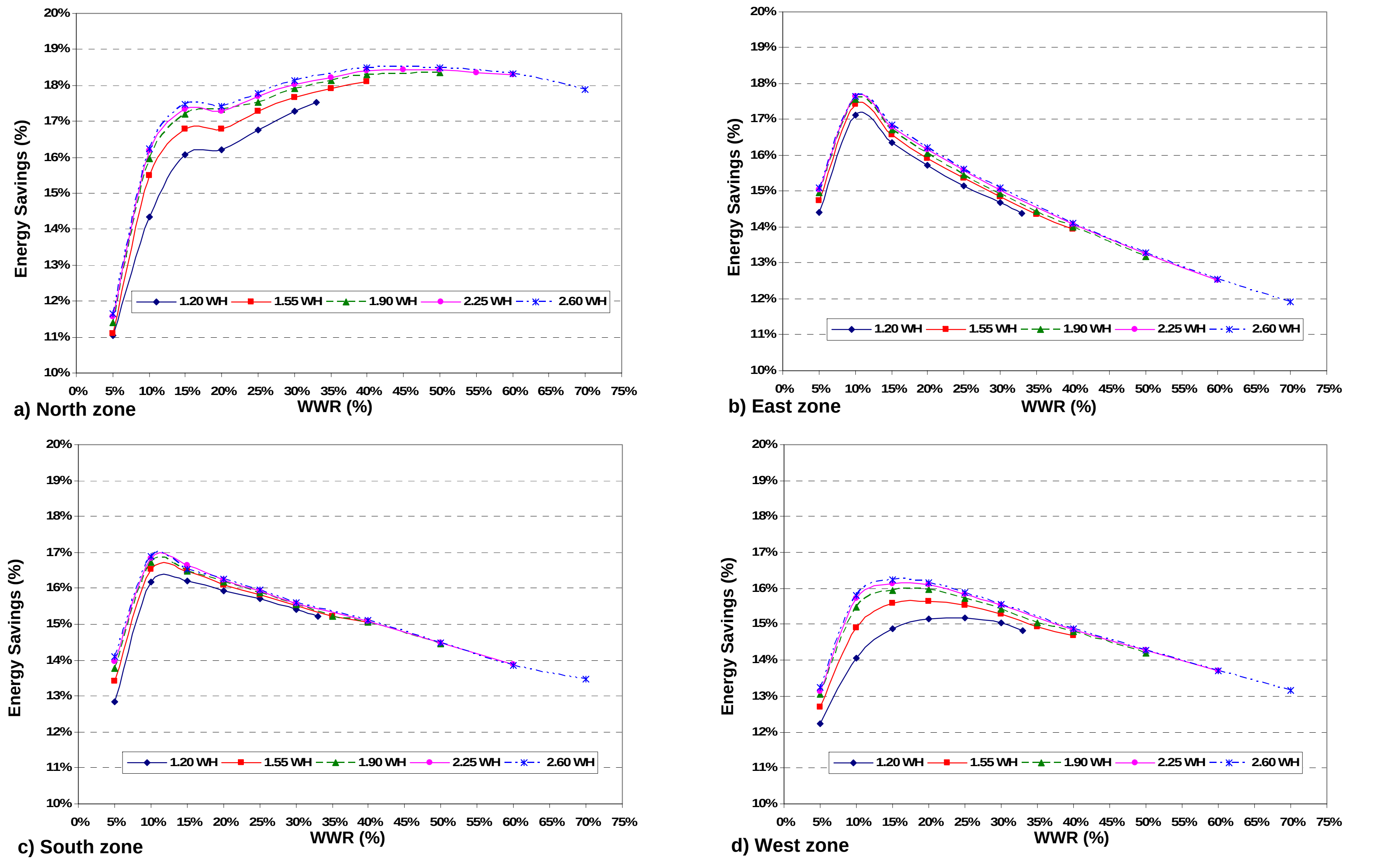



**Figure 4.9** Expected energy savings for various window heights – double-glazed clear – [a) North zone, b) East zone, c) South zone, and d) West zone]

## 4.5 The Impact of Various Floor Areas on Energy Performance

Previous findings were based on the simulation of a typical office building with a specific geometrical configuration as obtained from the survey results. As geometrical configuration impacts building exposure to outside environment and the area of exterior walls, it is important to investigate the impact of floor area on building energy performance due to the integration of daylighting and artificial lighting. The impact on both lighting and total energy consumption is investigated.

The base case model was a square shape with floor dimensions of $22 \times 22\ m^2$. Two alternative floor areas were investigated with dimensions of $26 \times 26\ m^2$ and $30 \times 30\ m^2$. The square shape of the building was maintained and the depth of the perimeter zones was kept at 7 m.

This investigation was conducted for the four principal zone orientations, double-glazed clear window, and 1.90 m window height. Different window areas were modeled, starting from 5% WWR up to the maximum, i.e. 50%. Results showed similar trends for the expected energy savings in both lighting energy consumption and total energy consumption. In addition, results revealed a slight difference in the obtained energy savings for the investigated floor areas.

### 4.5.1 Potential for Reduction in Lighting Energy Consumption

An investigation on the impact of the various floor areas on lighting energy consumption was carried out when daylighting and artificial lighting are integrated. The analysis was carried out for double-glazed clear window with a height of 1.9 m at different WWR and principal zone orientations.

**Figure 4.15** shows the expected lighting energy savings for various floor areas and different window areas. Results have demonstrated that there is only a slight difference in the expected reduction in the energy consumed by the artificial lighting system for all floor areas investigated.

It can be noticed from **Figure 4.15** that there is a small difference in lighting energy savings for small window areas, i.e. 5-15% WWR. However, this difference diminishes as window area is increased. From these results it can be concluded that the increase in floor area does seem to have a significant impact on the expected reduction in lighting energy consumption when daylighting is integrated with artificial lighting. Furthermore, it can be seen that the larger the window area, the higher the lighting energy savings for all floor areas.

Similar results were obtained for the other zone orientations. **Figure 4.16** illustrates the lighting energy savings for the south zone. It can be noticed that the lighting energy savings differ little at small window area and negligibly when the window area is increased.

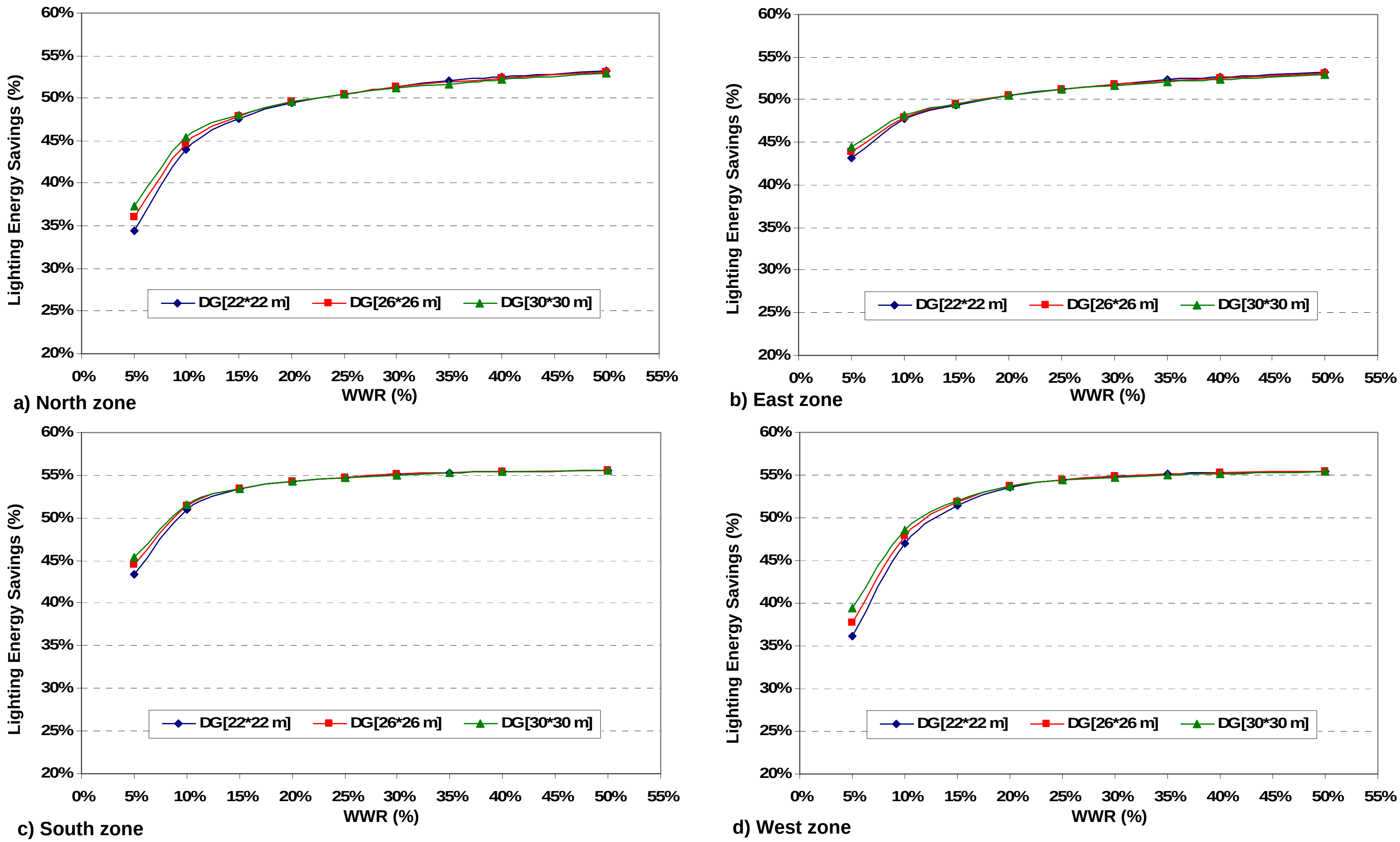



**Figure 4.10** Expected lighting energy savings for various floor areas – 1.90 m window height – double-glazed clear – [a) North zone, b) East zone, c) South zone, and d) West zone]

### 4.5.2 Total Energy Savings

A reduction in energy consumption can be achieved by the integration between daylighting and artificial lighting. Resulting energy savings when the floor area is enlarged were investigated, and the results are explained below. A double-glazed clear window with a height of 1.90 m was selected for this analysis.

Energy savings due to lighting integration for different building floor areas in the north zone are shown in **Figure 4.11.a**. There is only a small change in the energy savings when the floor area is increased from 22×22 $m^2$ to 30×30 $m^2$. This difference diminishes as the window area sets larger for all floor areas used.

The results show that the energy savings increase significantly from about 12% to almost 17% when the WWR is enlarged from 5% to 15% for all floor areas used. However, when the WWR is increased over 15%, energy savings are not substantially increased.

It can be concluded that the area of the zone floor has little impact on energy savings at lower WWR (5-15%) but no or little difference is experienced in energy savings at higher window-to-wall ratios.

A similar impact is obtained for differently oriented zones as shown in **Figure 4.11.b,** illustrating energy savings for the east zone. A small increase in energy savings is obtained when floor area is enlarged at a small WWR (5-10%), but a slight increase in energy savings is achieved at larger window area. The energy savings are higher when WWR is increased from 5% to 10%, but a continuous decrease can be noticed at larger windows for all floor areas used in this investigation.

Similar results were obtained for the south and west zones as shown in **Figure 4.11.c** and **Figure 4.11.d**. It can be noticed that there is almost a constant increase in energy savings for all WWRs, when the floor area is enlarged. The maximum energy savings can be achieved at 10-15% WWR and the energy savings gradually decrease at larger WWRs.

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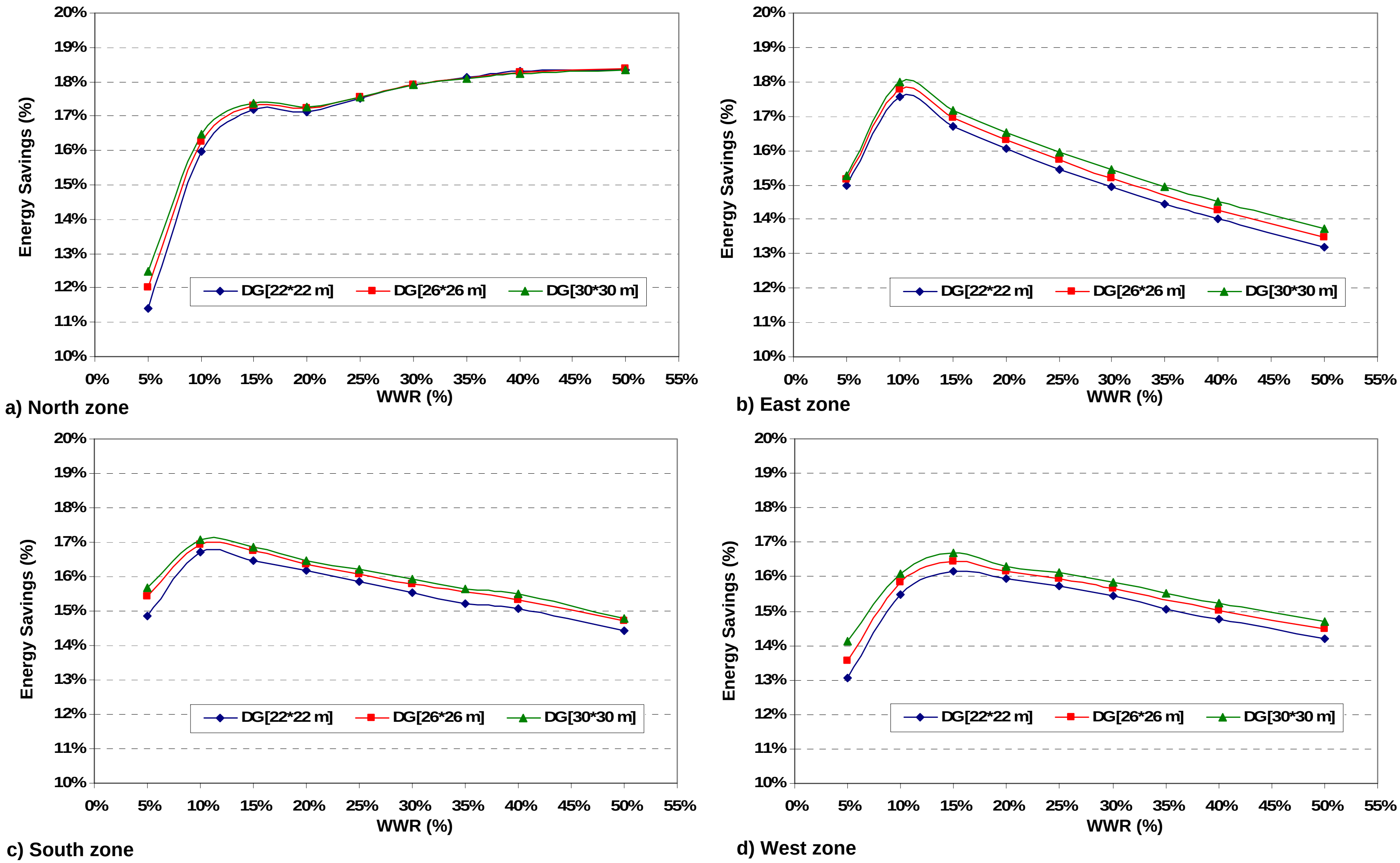



**Figure 4.11** Expected energy savings for various floor areas – double-glazed clear – 1.90 m window height – [a) North zone, b) East zone, c) South zone, and d) West zone]

## 4.6 Energy Savings due to Daylight Integration at Different Climatic Conditions

In Saudi Arabia, climatic conditions vary from one region to another depending on the geographical location and the availability of water bodies. Climatic conditions have a major influence on the amount of energy savings resulting from daylighting and artificial lighting integration, as they determine the availability of light and the amount of heat gain through fenestrations. In order to investigate the impact of climatic conditions on energy savings and to assess the possibility of applying the results of this study to other locations, these weather data files for Dhahran, Riyadh, and Jeddah were selected for comparison as they are all hot climates. This investigation was conducted for principal zone orientations, double-glazed clear window with a height of 1.90 m, and different WWRs.

The simulation results showed that there is a similar trend for energy savings variations with WWRs for all weather data used, with noticeable difference in the amount of energy savings. This difference is almost constant as the WWR increases. **Figure 4.12.a** shows the potential of energy savings for the north zone, different weather data, and different WWRs. It can be observed that the maximum energy saving is achieved for Riyadh weather conditions. It is followed by Jeddah, then by Dhahran. This may be because the availability of daylight varies according to the location of the city and its longitude and latitude and also the year-round variation of sky conditions for each city. Similar results for the other principal zone orientations are obtained, as depicted in **Figure 4.12.**

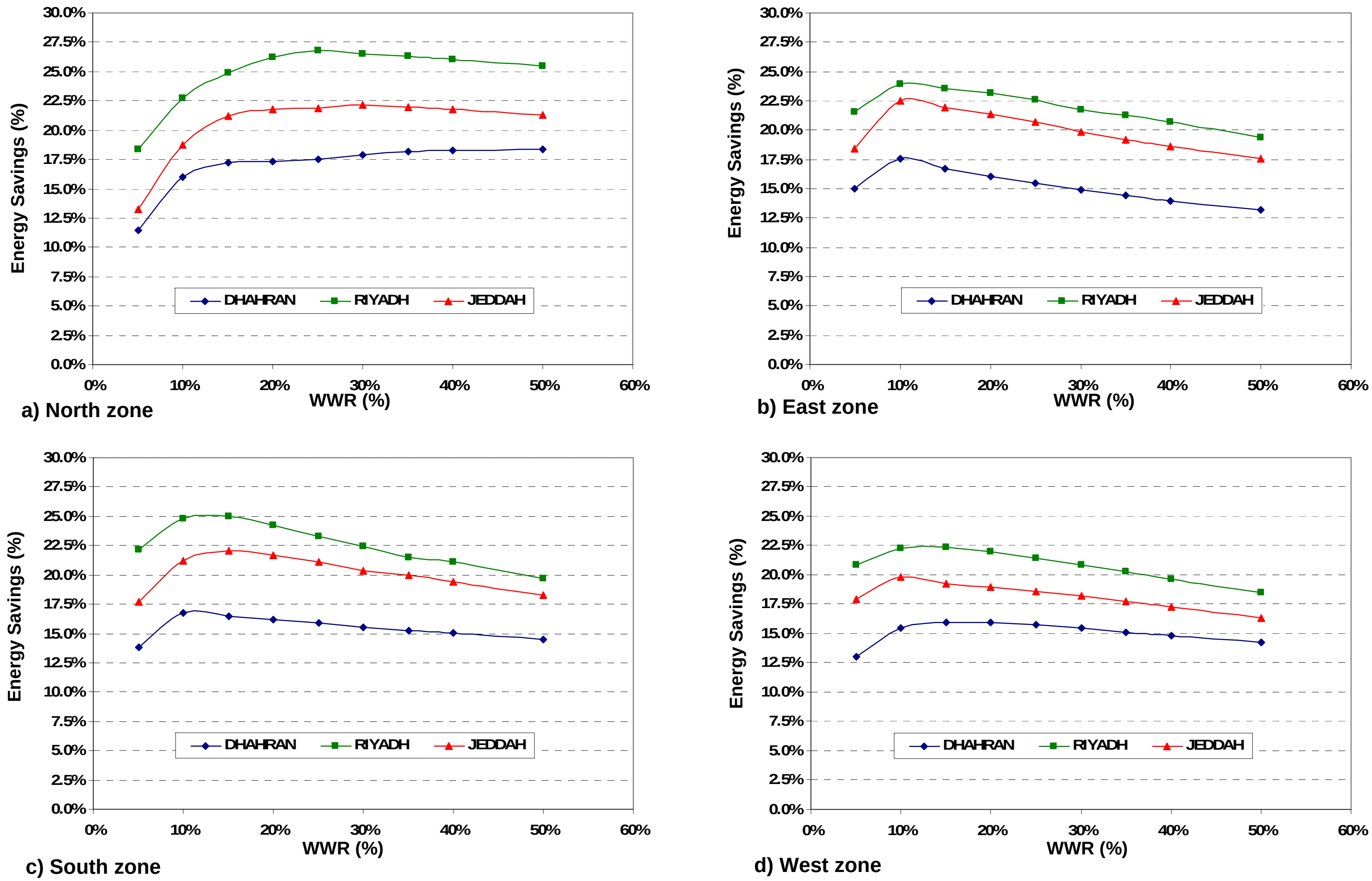



**Figure 4.12** Expected energy savings for various weather conditions – double-glazed clear – 1.90 m window height – [a) North zone, b) East zone, c) South zone, and d) West zone]

## 4.7 Development of a Design Tool

One of the main objectives of this research is to develop a design tool to assist in the energy-efficient window design through the integration of daylighting with artificial lighting in office buildings. This is done with the objective of providing sufficient natural lighting into the built space with low energy consumption by utilizing a lighting control strategy to control the artificial lighting. The design tool aims to help a designer to easily select the best window area, window height, and type of glazing for a window for each principal zone orientation when designing office buildings in hot-humid climates.

The window design at which there is a maximum energy saving can be considered the ideal, as the required illumination level is maintained during the occupied period. This is done by using either the available daylighting or the installed artificial lighting.

The main indicator to compare window design alternatives is the energy savings expected from the integration of daylighting and artificial lighting. Data on energy savings (obtained from the simulation of various window parameters, as explained in the previous sections) were utilized to develop this design tool.

The design tool is presented in two different ways. First, it is presented in a set of graphs which illustrate the energy savings for the principal zone orientations, various window heights, various glazing types, and different WWRs. The second method is by presenting the energy savings results as a set of four tables, each representing a principal zone orientation. The tables and graphs are developed for a square building with an average floor area of 484 $m^2$ i.e. 22×22 $m^2$ dimensions, but they can be used for evaluating the relative energy performance and energy savings for larger floor areas with similar geometrical configuration.

The main parameters utilized in each table and graph are:

1) Zone orientation (North – East – South – West)
2) Window height (1.20 – 1.55 – 1.90 – 2.25 – 2.6) m.
3) Type of glazing ( Single clear – Double clear – Double clear low-e – Double clear with heat mirror)
4) Window to wall ratio (WWR)

### 4.7.1 Utilization of Developed Graphs for Selecting the Ideal Window

**Figures 4.13, 4.14, 4.15, 4.16,** and **4.17** illustrate the expected energy savings for the principal zone orientations, various glazing types, and for the selected window heights i.e. 1.20 m, 1.55 m, 1.90 m, 2.25 m, and 2.60 m.

Providing the results graphically is preferred by designers as it has many advantages, such as the ability to obtain information easily from graphs and to compare different window design alternatives faster. Theses graphs can be used to identify the expected energy savings for a specific window design or to define the best window design according to the maximum energy savings. The following examples will explain how such graphs can be used either to define the expected energy savings or to identify the ideal window design.

Suppose a window with these parameters is designed in the east zone:

- 2.25 m window height
- Double glazed clear
- 20% WWR

Energy savings of about 16% can be expected when daylight is integrated with artificial lighting, as shown in **Figure 4.16**. However, to identify the ideal window design for a specific zone orientation, e.g. the east zone, the window height should be specified. For example, if the window height is assumed to be 1.55 m, the highest energy savings can be seen at 20% WWR with double-glazed clear heat-mirror glass, as shown in **Figure 4.14**. However, at 1.90 m window height, the maximum energy savings can be found at a window with 10% WWR and double-glazed clear low-e, as illustrated in **Figure 4.15**.

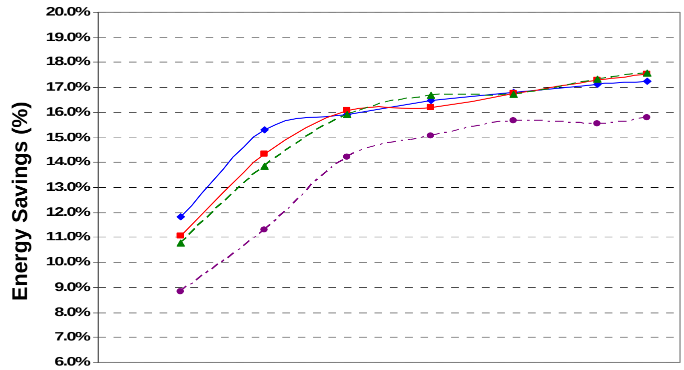
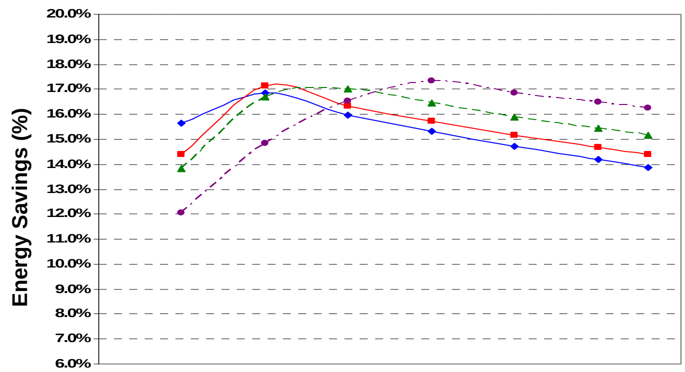
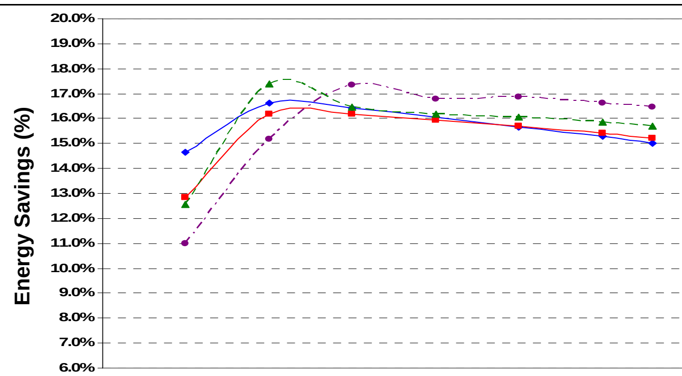
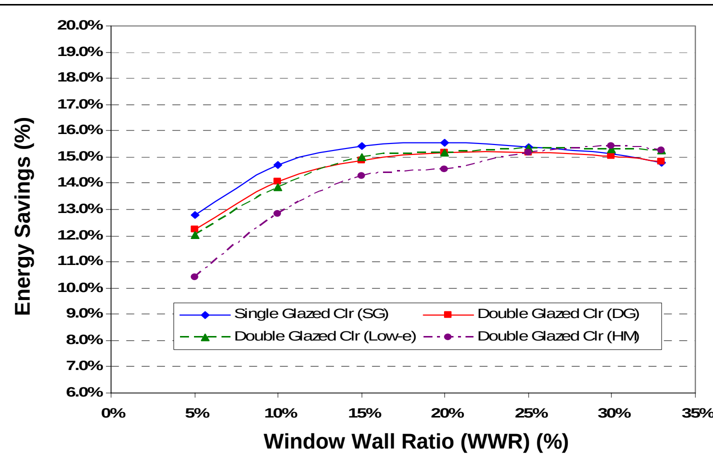
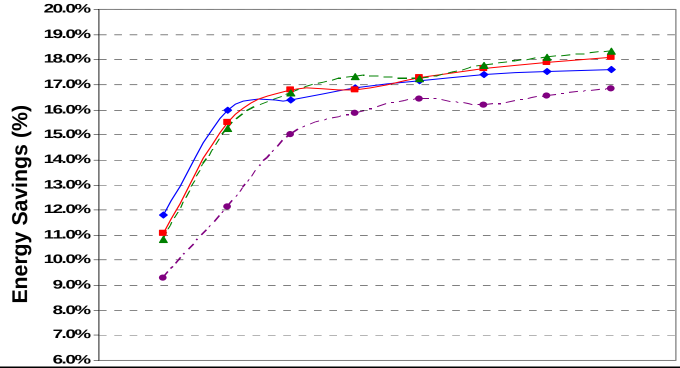
| **Potential of Energy Savings For Principal Zone Orientations – <u>1.20 Window Height</u> – Various Type of Glazing** | |
|---|---|
| **North** |  |
| **East** |  |
| **South** |  |
| **West** |  |



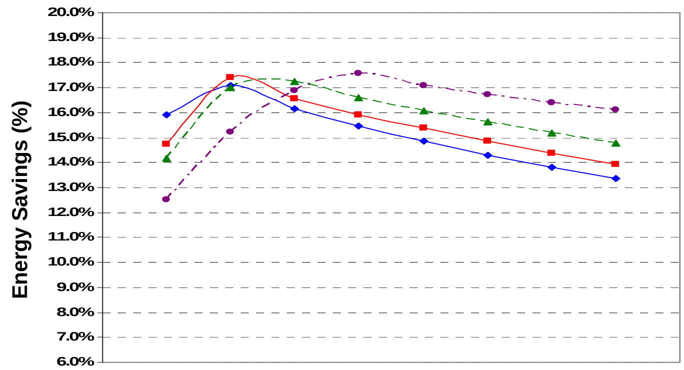
**Figure 4.13** Potential of energy savings for 1.20 m window height

**Potential of Energy Savings For Principal Zone Orientations – <u>1.55 Window Height</u> – Various Type of Glazing**

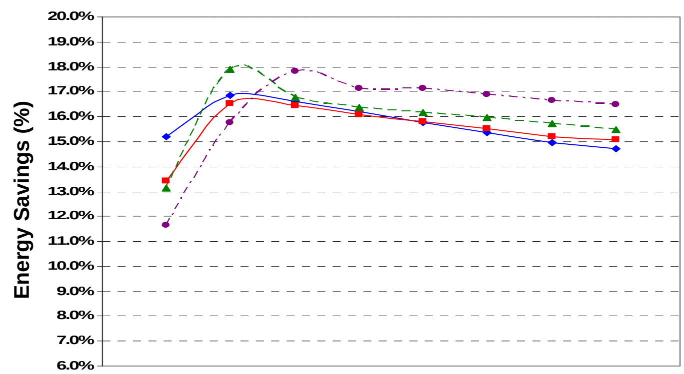
**North**




**East**




**South**




**West**

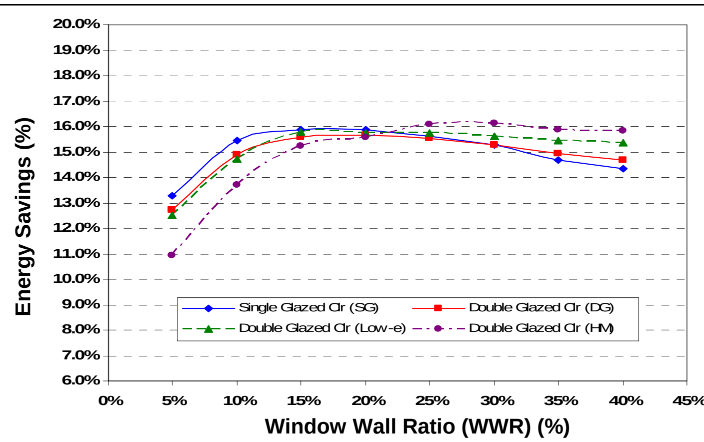



**Figure 4.14** Potential of energy savings for 1.55 m window height

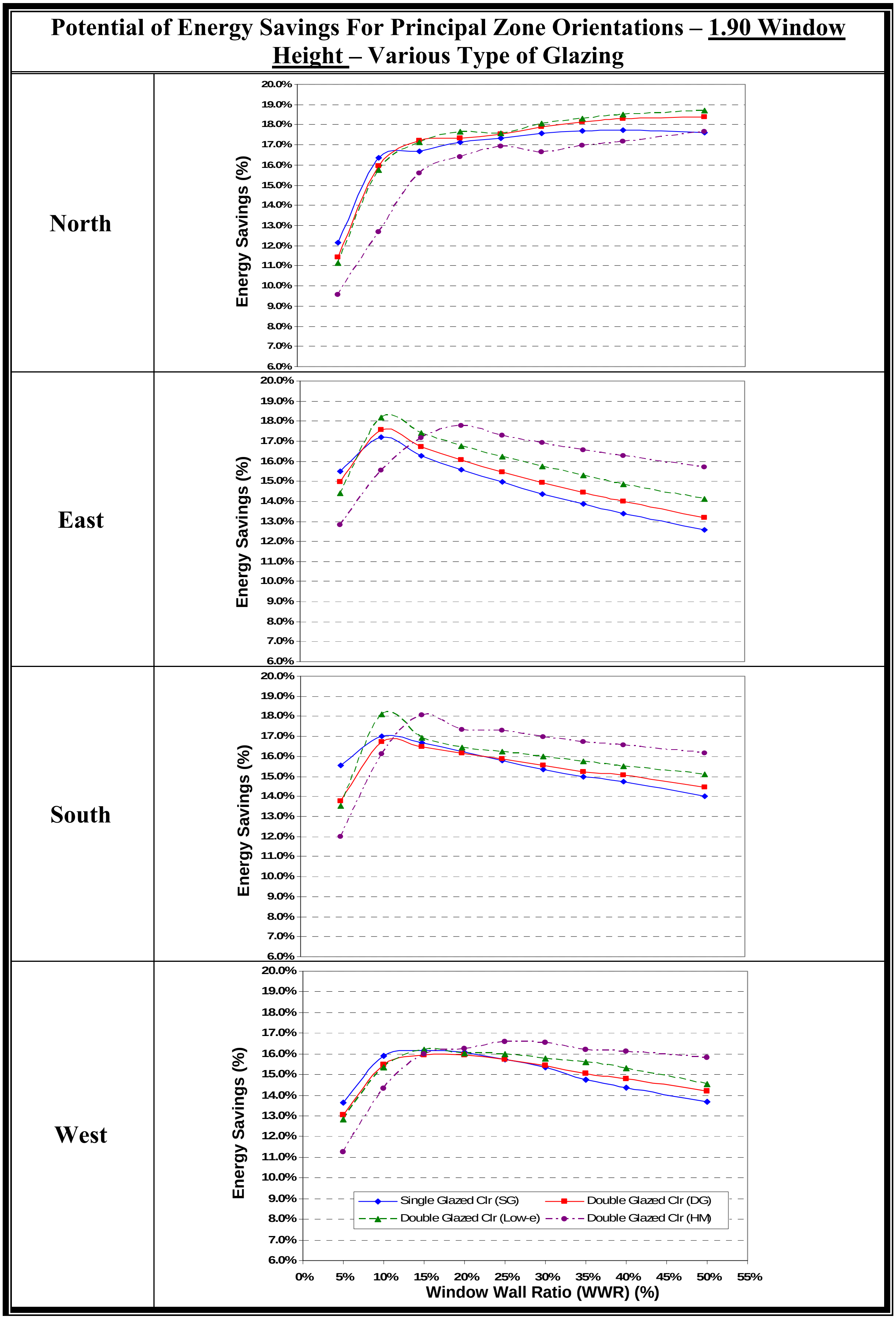



**Figure 4.15** Potential of energy savings for 1.90 m window height

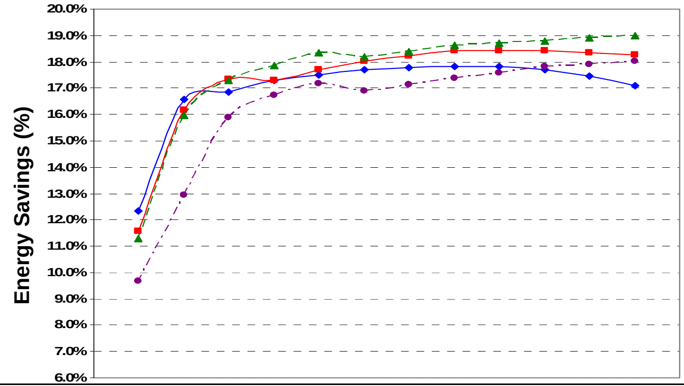
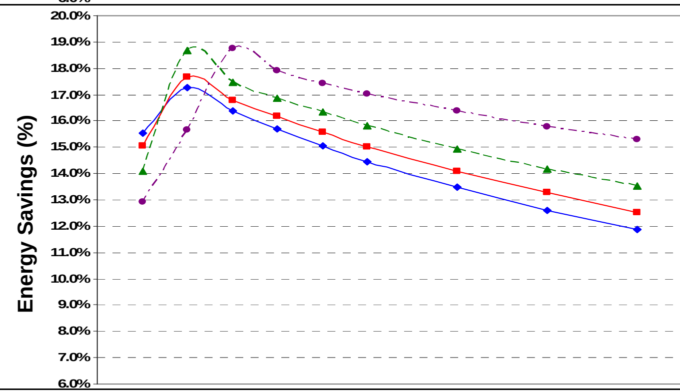
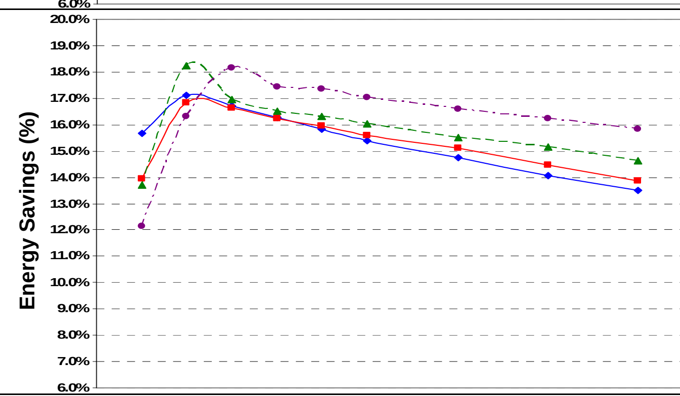
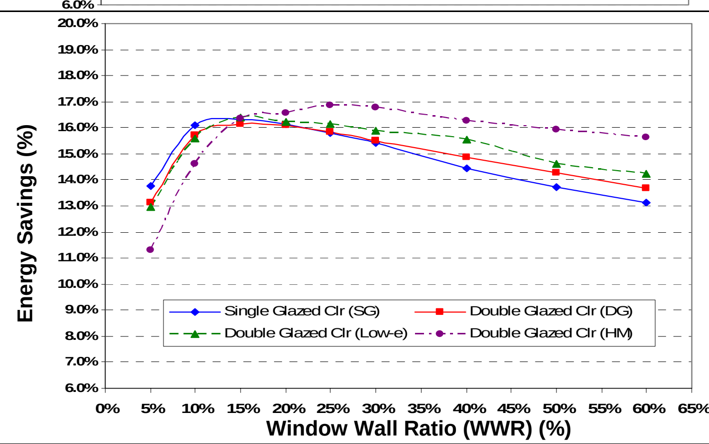
| **Potential of Energy Savings For Principal Zone Orientations – 2.25 Window Height – Various Type of Glazing** | |
|---|---|
| **North** |   |
| **East** |   |
| **South** |   |
| **West** |   |

**Figure 4.16** Potential of energy savings for 2.25 m window height

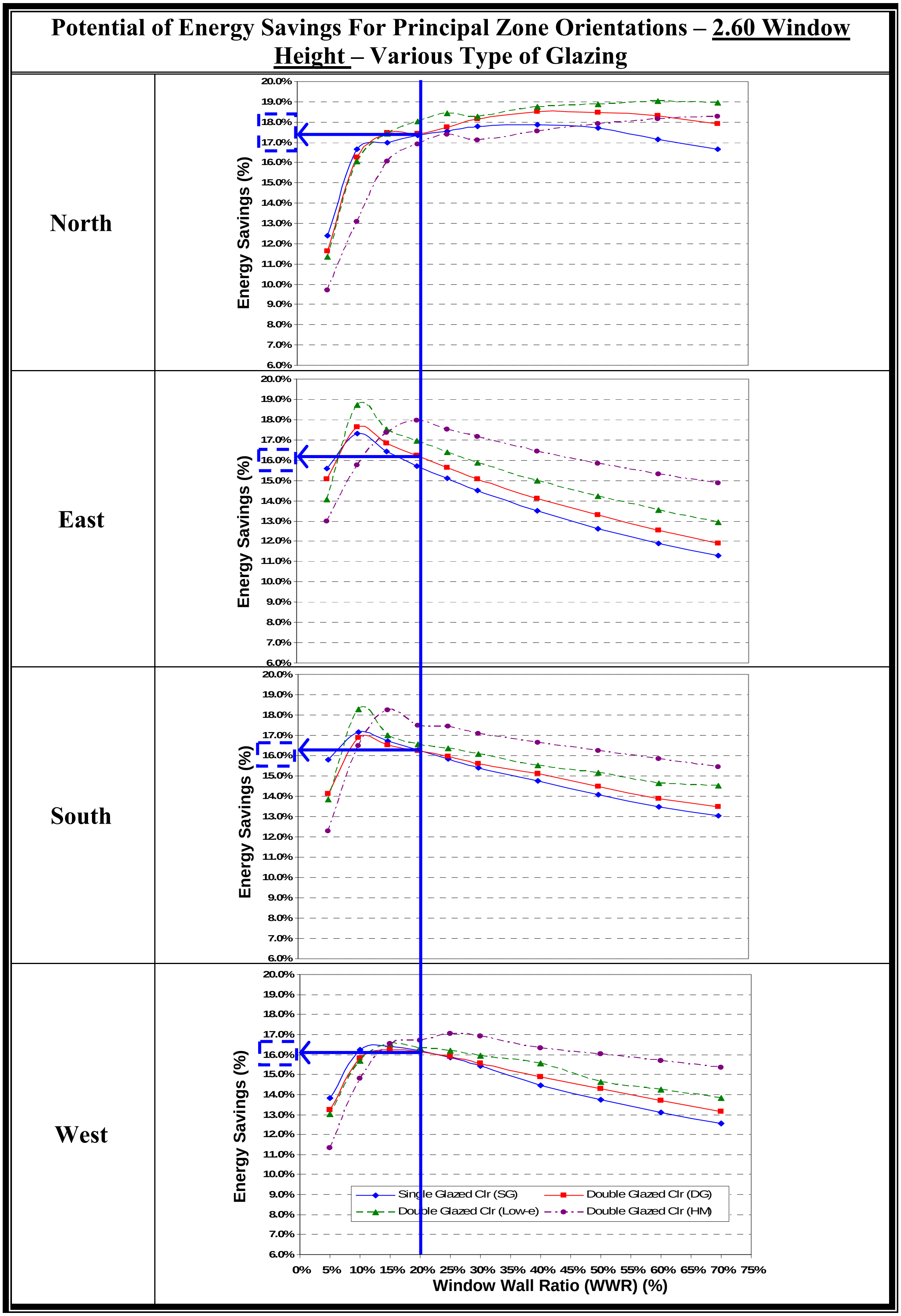



**Figure 4.17** Potential of energy savings for 2.60 m window height

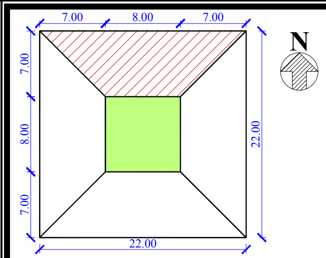
### 4.7.2 Utilization of Developed Tables for Selecting the Ideal Window

Tables provide more precise energy saving results, as these can be obtained directly from the developed tables once the specific window design parameters are defined. Four tables were developed for each principal zone orientation, and in the following paragraphs examples are explained to show how these tables can be used. Tables can be used either to identify the resulting energy savings for a specific window design or to define the best window design according to the maximum energy savings.

In order to identify the expected energy savings for a specific window, the designer needs to define the main input parameters that are used in these tables, including zone orientation, window height, type of glazing and WWR. For example, if a double-glazed clear window with a height of 1.90 m and WWR of 30% is used, the expected energy savings from the integration of daylighting and artificial lighting is about 18%, as illustrated in **Table 4.3**.

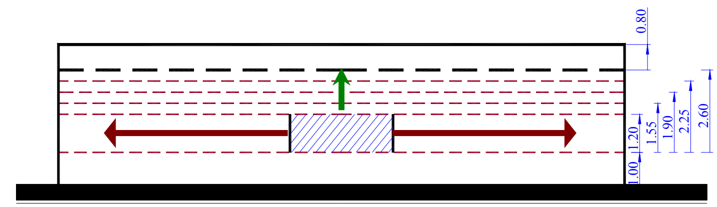
On the other hand, these tables can be used to identify the best window design which has the highest possible energy savings. For example, from **Table 4.3** it is noticed that the maximum energy savings that can be achieved for the north space is about 19%. This can be obtained by two different window designs. First, it can be achieved with double-glazed clear low-e window with a height of 2.25 m and 55-60% WWR. Alternatively, it can be obtained with double-glazed clear low-e window with a height of 2.60 m and 50-70% WWR. **Table 4.4, Table 4.5** and **Table 4.6** show the expected energy savings for the other principal orientations (east, south and west). These tables can also be used as explained in the previous examples.

**Table 4.3** Potential of energy savings for the north zone




**Energy Savings For Various Window Heights, Window to Wall Ratios and Glazing Types**

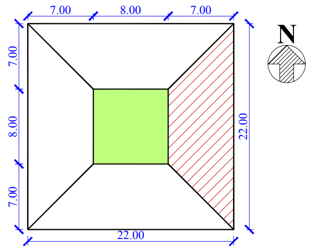
North Zone – 1.00 m Window Sill




| WWR[1] (%) | 1.20 WH[2] | | | | 1.55 WH | | | | 1.90 WH | | | | 2.25 WH | | | | 2.60 WH | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | SG[3] | DG[4] | Low-e[5] | HM[6] | SG | DG | Low-e | HM | SG | DG | Low-e | HM | SG | DG | Low-e | HM | SG | DG | Low-e | HM |
| *5%* | 11.8% | 11.0% | 10.8% | 8.8% | 11.8% | 11.1% | 10.8% | 9.3% | 12.2% | 11.4% | 11.1% | 9.6% | 12.3% | 11.6% | 11.3% | 9.7% | 12.4% | 11.6% | 11.4% | 9.7% |
| *10%* | 15.3% | 14.3% | 13.9% | 11.3% | 16.0% | 15.5% | 15.3% | 12.1% | 16.4% | 16.0% | 15.7% | 12.7% | 16.6% | 16.2% | 16.0% | 12.9% | 16.7% | 16.2% | 16.1% | 13.1% |
| *15%* | 15.9% | 16.1% | 15.9% | 14.2% | 16.4% | 16.8% | 16.7% | 15.0% | 16.7% | 17.2% | 17.1% | 15.6% | 16.9% | 17.3% | 17.3% | 15.9% | 17.0% | 17.5% | 17.4% | 16.1% |
| *20%* | 16.5% | 16.2% | 16.7% | 15.1% | 16.9% | 16.8% | 17.3% | 15.8% | 17.1% | 17.1% | 17.7% | 16.4% | 17.3% | 17.3% | 17.9% | 16.7% | 17.3% | 17.4% | 18.0% | 16.9% |
| *25%* | 16.8% | 16.8% | 16.7% | 15.7% | 17.1% | 17.3% | 17.2% | 16.4% | 17.3% | 17.5% | 17.6% | 16.9% | 17.5% | 17.7% | 18.3% | 17.2% | 17.6% | 17.8% | 18.4% | 17.4% |
| *30%* | 17.1% | 17.3% | 17.3% | 15.5% | 17.4% | 17.7% | 17.8% | 16.2% | 17.6% | 17.9% | 18.0% | 16.7% | 17.7% | 18.0% | 18.2% | 16.9% | 17.8% | 18.1% | 18.3% | 17.1% |
| *35%* | 17.3% | 17.5% | 17.6% | 15.8% | 17.5% | 17.9% | 18.1% | 16.5% | 17.7% | 18.1% | 18.3% | 16.9% | 17.8% | 18.2% | 18.4% | 17.1% | 17.8% | 18.3% | 18.5% | 17.3% |
| *40%* | | | | | 17.6% | 18.1% | 18.3% | 16.8% | 17.7% | 18.3% | 18.5% | 17.2% | 17.8% | 18.4% | 18.6% | 17.4% | 17.9% | 18.5% | 18.8% | 17.5% |
| *45%* | | | | | | | | | 17.7% | 18.3% | 18.6% | 17.4% | 17.8% | 18.4% | 18.7% | 17.6% | 17.8% | 18.5% | 18.8% | 17.7% |
| *50%* | | | | | | | | | 17.6% | 18.4% | 18.7% | 17.7% | 17.7% | 18.4% | 18.8% | 17.8% | 17.7% | 18.5% | 18.9% | 17.9% |
| *55%* | | | | | | | | | | | | | 17.4% | 18.4% | 18.9% | 17.9% | 17.4% | 18.4% | 19.0% | 18.0% |
| *60%* | | | | | | | | | | | | | 17.1% | 18.3% | 19.0% | 18.0% | 17.1% | 18.3% | 19.1% | 18.1% |
| *65%* | | | | | | | | | | | | | | | | | 16.9% | 18.1% | 19.0% | 18.2% |
| *70%* | | | | | | | | | | | | | | | | | 16.7% | 17.9% | 18.9% | 18.3% |

1. (WWR): Window-to-wall ratio
2. (WH): Window Height
3. (SG): Single-glazed clear 6mm
4. (DG): Double-glazed clear with air space 6/12/6 mm
5. (Low-e): Double-glazed clear Low-e with air space 6/12/6 mm
6. (HM): Double-glazed clear with heat-mirror and air space 6/12/6 mm

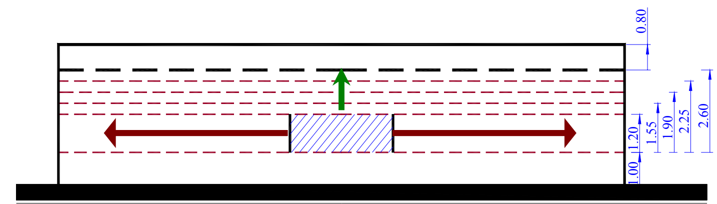
**Table 4.4** Potential of energy savings for the east zone




**Energy Savings For Various Window Heights,**

**Window to Wall Ratios and Glazing Types**

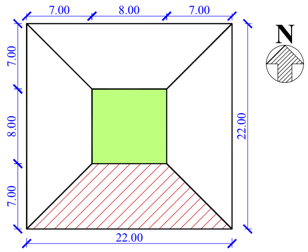
East Zone – 1.00 m Window Sill




| WWR[1] (%) | 1.20 WH[2] | | | | 1.55 WH | | | | 1.90 WH | | | | 2.25 WH | | | | 2.60 WH | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | SG[3] | DG[4] | Low-e[5] | HM[6] | SG | DG | Low-e | HM | SG | DG | Low-e | HM | SG | DG | Low-e | HM | SG | DG | Low-e | HM |
| 5% | 15.6% | 14.4% | 13.8% | 12.0% | 15.9% | 14.8% | 14.2% | 12.5% | 15.5% | 15.0% | 14.4% | 12.8% | 15.6% | 15.0% | 14.1% | 12.9% | 15.6% | 15.1% | 14.1% | 13.0% |
| 10% | 16.9% | 17.1% | 16.7% | 14.8% | 17.1% | 17.4% | 17.0% | 15.2% | 17.2% | 17.6% | 18.2% | 15.5% | 17.3% | 17.6% | 18.7% | 15.6% | 17.3% | 17.6% | 18.7% | 15.7% |
| 15% | 16.0% | 16.3% | 17.0% | 16.5% | 16.2% | 16.6% | 17.3% | 16.9% | 16.3% | 16.7% | 17.4% | 17.2% | 16.4% | 16.8% | 17.5% | 18.7% | 16.4% | 16.8% | 17.5% | 17.4% |
| 20% | 15.3% | 15.7% | 16.5% | 17.3% | 15.5% | 15.9% | 16.6% | 17.6% | 15.6% | 16.1% | 16.7% | 17.8% | 15.7% | 16.2% | 16.9% | 17.9% | 15.7% | 16.2% | 16.9% | 18.0% |
| 25% | 14.7% | 15.1% | 15.9% | 16.9% | 14.9% | 15.4% | 16.1% | 17.1% | 14.9% | 15.5% | 16.2% | 17.3% | 15.1% | 15.6% | 16.4% | 17.4% | 15.1% | 15.6% | 16.4% | 17.5% |
| 30% | 14.2% | 14.7% | 15.4% | 16.5% | 14.3% | 14.9% | 15.6% | 16.7% | 14.4% | 14.9% | 15.7% | 16.9% | 14.5% | 15.0% | 15.8% | 17.0% | 14.5% | 15.1% | 15.9% | 17.1% |
| 35% | 13.9% | 14.4% | 15.1% | 16.3% | 13.8% | 14.4% | 15.2% | 16.4% | 13.9% | 14.4% | 15.3% | 16.6% | 14.0% | 14.6% | 15.4% | 16.7% | 14.0% | 14.6% | 15.4% | 16.8% |
| 40% | | | | | 13.4% | 13.9% | 14.8% | 16.1% | 13.4% | 14.0% | 14.9% | 16.2% | 13.5% | 14.1% | 14.9% | 16.4% | 13.5% | 14.1% | 15.0% | 16.4% |
| 45% | | | | | | | | | 13.0% | 13.6% | 14.5% | 16.0% | 13.0% | 13.7% | 14.6% | 16.1% | 13.1% | 13.7% | 14.6% | 16.1% |
| 50% | | | | | | | | | 12.6% | 13.2% | 14.1% | 15.7% | 12.6% | 13.3% | 14.2% | 15.8% | 12.6% | 13.3% | 14.2% | 15.8% |
| 55% | | | | | | | | | | | | | 12.3% | 12.9% | 13.8% | 15.5% | 12.3% | 12.9% | 13.9% | 15.6% |
| 60% | | | | | | | | | | | | | 11.9% | 12.5% | 13.5% | 15.3% | 11.9% | 12.6% | 13.5% | 15.3% |
| 65% | | | | | | | | | | | | | | | | | 11.6% | 12.2% | 13.2% | 15.1% |
| 70% | | | | | | | | | | | | | | | | | 11.3% | 11.9% | 12.9% | 14.9% |

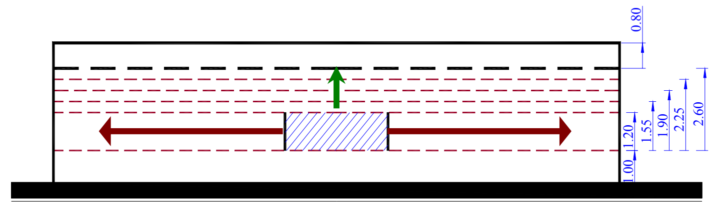
7. (WWR): Window-to-wall ratio
8. (WH): Window Height
9. (SG): Single-glazed clear 6mm
10. (DG): Double-glazed clear with air space 6/12/6 mm
11. (Low-e): Double-glazed clear Low-e with air space 6/12/6 mm
12. (HM): Double-glazed clear with heat-mirror and air space 6/12/6 mm

**Table 4.5** Potential of energy savings for the south zone




**Energy Savings For Various Window Heights, Window to Wall Ratios and Glazing Types**

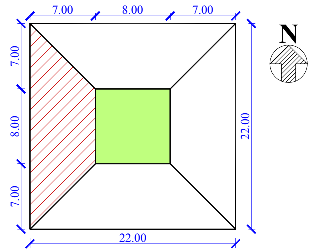
South Zone – 1.00 m Window Sill




| WWR[1] (%) | 1.20 WH[2] | | | | 1.55 WH | | | | 1.90 WH | | | | 2.25 WH | | | | 2.60 WH | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | SG[3] | DG[4] | Low-e[5] | HM[6] | SG | DG | Low-e | HM | SG | DG | Low-e | HM | SG | DG | Low-e | HM | SG | DG | Low-e | HM |
| *5%* | 14.7% | 12.8% | 12.6% | 11.0% | 15.2% | 13.4% | 13.2% | 11.6% | 15.5% | 13.8% | 13.5% | 12.0% | 15.7% | 14.0% | 13.7% | 12.1% | 15.8% | 14.1% | 13.8% | 12.3% |
| *10%* | 16.6% | 16.2% | 17.4% | 15.2% | 16.9% | 16.5% | 17.9% | 15.7% | 17.0% | 16.7% | 18.1% | 16.1% | 17.1% | 16.8% | 18.2% | 16.3% | 17.2% | 16.9% | 18.3% | 16.5% |
| *15%* | 16.4% | 16.2% | 16.5% | 17.3% | 16.6% | 16.5% | 16.8% | 17.8% | 16.7% | 16.5% | 16.9% | 18.1% | 16.7% | 16.6% | 16.9% | 18.2% | 16.7% | 16.5% | 17.0% | 18.2% |
| *20%* | 16.1% | 15.9% | 16.2% | 16.8% | 16.2% | 16.1% | 16.4% | 17.1% | 16.2% | 16.2% | 16.4% | 17.3% | 16.3% | 16.2% | 16.5% | 17.4% | 16.3% | 16.3% | 16.5% | 17.5% |
| *25%* | 15.7% | 15.7% | 16.0% | 16.9% | 15.8% | 15.8% | 16.2% | 17.1% | 15.8% | 15.9% | 16.3% | 17.3% | 15.8% | 15.9% | 16.3% | 17.4% | 15.8% | 16.0% | 16.3% | 17.4% |
| *30%* | 15.3% | 15.4% | 15.8% | 16.6% | 15.4% | 15.5% | 16.0% | 16.9% | 15.4% | 15.5% | 16.0% | 17.0% | 15.4% | 15.6% | 16.0% | 17.0% | 15.4% | 15.6% | 16.1% | 17.1% |
| *35%* | 15.0% | 15.2% | 15.7% | 16.5% | 15.0% | 15.2% | 15.7% | 16.7% | 15.0% | 15.2% | 15.8% | 16.7% | 15.1% | 15.3% | 15.8% | 16.8% | 15.1% | 15.4% | 15.8% | 16.9% |
| *40%* | | | | | 14.7% | 15.1% | 15.5% | 16.5% | 14.7% | 15.1% | 15.5% | 16.6% | 14.7% | 15.1% | 15.5% | 16.6% | 14.8% | 15.1% | 15.5% | 16.6% |
| *45%* | | | | | | | | | 14.4% | 14.8% | 15.3% | 16.4% | 14.4% | 14.8% | 15.3% | 16.4% | 14.4% | 14.8% | 15.3% | 16.4% |
| *50%* | | | | | | | | | 14.0% | 14.4% | 15.1% | 16.2% | 14.1% | 14.5% | 15.1% | 16.2% | 14.1% | 14.5% | 15.2% | 16.2% |
| *55%* | | | | | | | | | | | | | 13.8% | 14.2% | 14.9% | 16.0% | 13.8% | 14.2% | 14.9% | 16.0% |
| *60%* | | | | | | | | | | | | | 13.5% | 13.9% | 14.6% | 15.8% | 13.5% | 13.9% | 14.6% | 15.8% |
| *65%* | | | | | | | | | | | | | | | | | 13.3% | 13.7% | 14.6% | 15.6% |
| *70%* | | | | | | | | | | | | | | | | | 13.0% | 13.5% | 14.5% | 15.4% |

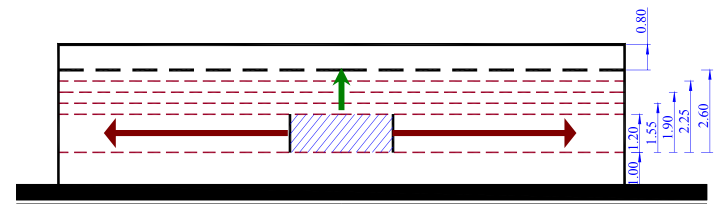
13. (WWR): Window-to-wall ratio
14. (WH): Window Height
15. (SG): Single-glazed clear 6mm
16. (DG): Double-glazed clear with air space 6/12/6 mm
17. (Low-e): Double-glazed clear Low-e with air space 6/12/6 mm
18. (HM): Double-glazed clear with heat-mirror and air space 6/12/6 mm

**Table 4.6** Potential of energy savings for the west zone




**Energy Savings For Various Window Heights, Window to Wall Ratios and Glazing Types**

West Zone – 1.00 m Window Sill




| WWR[1] (%) | 1.20 WH[2] | | | | 1.55 WH | | | | 1.90 WH | | | | 2.25 WH | | | | 2.60 WH | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | SG[3] | DG[4] | Low-e[5] | HM[6] | SG | DG | Low-e | HM | SG | DG | Low-e | HM | SG | DG | Low-e | HM | SG | DG | Low-e | HM |
| *5%* | 12.8% | 12.2% | 12.0% | 10.4% | 13.3% | 12.7% | 12.5% | 10.9% | 13.6% | 13.0% | 12.8% | 11.2% | 13.8% | 13.1% | 13.0% | 11.3% | 13.8% | 13.2% | 13.0% | 11.3% |
| *10%* | 14.7% | 14.0% | 13.9% | 12.8% | 15.4% | 14.9% | 14.7% | 13.7% | 15.9% | 15.5% | 15.3% | 14.3% | 16.1% | 15.7% | 15.6% | 14.6% | 16.3% | 15.8% | 15.7% | 14.8% |
| *15%* | 15.4% | 14.9% | 15.0% | 14.3% | 15.9% | 15.6% | 15.8% | 15.3% | 16.2% | 15.9% | 16.2% | 16.0% | 16.3% | 16.1% | 16.4% | 16.3% | 16.4% | 16.2% | 16.5% | 16.5% |
| *20%* | 15.6% | 15.1% | 15.1% | 14.5% | 15.9% | 15.7% | 15.7% | 15.6% | 16.1% | 16.0% | 16.0% | 16.2% | 16.2% | 16.1% | 16.2% | 16.5% | 16.2% | 16.2% | 16.3% | 16.7% |
| *25%* | 15.4% | 15.2% | 15.3% | 15.1% | 15.6% | 15.5% | 15.7% | 16.1% | 15.7% | 15.7% | 16.0% | 16.6% | 15.8% | 15.8% | 16.1% | 16.8% | 15.8% | 15.9% | 16.2% | 17.0% |
| *30%* | 15.1% | 15.0% | 15.3% | 15.4% | 15.3% | 15.3% | 15.6% | 16.1% | 15.3% | 15.4% | 15.8% | 16.6% | 15.4% | 15.5% | 15.9% | 16.8% | 15.5% | 15.6% | 15.9% | 16.9% |
| *35%* | 14.8% | 14.8% | 15.2% | 15.3% | 14.7% | 14.9% | 15.5% | 15.9% | 14.7% | 15.0% | 15.6% | 16.2% | 14.9% | 15.2% | 15.7% | 16.5% | 15.0% | 15.2% | 15.8% | 16.6% |
| *40%* | | | | | 14.3% | 14.7% | 15.3% | 15.8% | 14.4% | 14.8% | 15.3% | 16.1% | 14.4% | 14.9% | 15.5% | 16.2% | 14.5% | 14.9% | 15.6% | 16.3% |
| *45%* | | | | | | | | | 14.0% | 14.5% | 14.9% | 16.0% | 14.1% | 14.6% | 15.1% | 16.1% | 14.1% | 14.6% | 15.1% | 16.2% |
| *50%* | | | | | | | | | 13.7% | 14.2% | 14.6% | 15.8% | 13.7% | 14.3% | 14.6% | 15.9% | 13.7% | 14.3% | 14.6% | 16.0% |
| *55%* | | | | | | | | | | | | | 13.4% | 14.0% | 14.4% | 15.8% | 13.4% | 14.0% | 14.4% | 15.8% |
| *60%* | | | | | | | | | | | | | 13.1% | 13.7% | 14.2% | 15.6% | 13.1% | 13.7% | 14.2% | 15.7% |
| *65%* | | | | | | | | | | | | | | | | | 12.8% | 13.4% | 14.0% | 15.5% |
| *70%* | | | | | | | | | | | | | | | | | 12.5% | 13.2% | 13.8% | 15.3% |

19. (WWR): Window-to-wall ratio
20. (WH): Window Height
21. (SG): Single-glazed clear 6mm
22. (DG): Double-glazed clear with air space 6/12/6 mm
23. (Low-e): Double-glazed clear Low-e with air space 6/12/6 mm
24. (HM): Double-glazed clear with heat-mirror and air space 6/12/6 mm

# CHAPTER FIVE

# SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

## 5.1 Summary and Conclusions

In Saudi Arabia, office buildings are the major consumer of electric energy. Their lighting systems account for a large portion of their total energy consumption. To conserve energy in buildings, many strategies can be applied, including the integration of daylighting with artificial lighting through lighting controls. Energy savings resulting from this strategy mean not only lower lighting energy consumption, but also less cooling energy consumption and the potential for a smaller air-conditioning system. Window design is crucial when daylight and artificial lighting are integrated. Large windows may allow more daylight, but large glazed areas may also allow excessive heat gain or loss. The optimum scenario to be specified is a window with a balance between lighting provision and energy consumed by lighting and cooling systems. The main objectives of this study were to investigate the impact of daylight integration on office buildings' energy performance, and subsequently to develop a design tool and guidelines to assist in energy-efficient integration of daylight and artificial lighting for different window areas, window heights, glazing types, and principal zone orientations. In order to achieve these objectives, the study comprises many phases: a literature review; a survey questionnaire to identify the design practices of envelope design and lighting requirements in office buildings; a base case simulated with and without daylight integration; and an analysis of the simulation results.

From the review of literature, it was found that daylight is desirable by most office buildings' occupants. This is because daylight provides high illuminance, good conditions for vision, and a view to the outside environment. Studies have demonstrated that daylight is essential for office buildings' occupants from different aspects, and these include:

- Daylight is highly preferred by many office buildings' occupants
- Daylight can help to maintain the occupants' health
- The utilization of daylight may increase the productivity of buildings' occupants

It was demonstrated that the integration of daylight with artificial lighting can result in a clear reduction in the lighting energy consumption and total energy consumption. This reduction in lighting energy consumption varies and can exceed 60% of the energy consumed by the lighting system. It was also found that the total energy savings vary for different studies, and a reduction of about 30% can be achieved in many cases. Another advantage of daylight utilization is the reduction in building thermal load. The integration of daylight with artificial lighting will reduce the use of artificial lighting, and it will subsequently reduce the building thermal load associated with the lighting system, and this will result in a smaller air-conditioning system.

The impact of different window characteristics on the energy performance of office buildings was reviewed. It was found that the increase in window area results in a higher energy saving. It is also proved that a glazing type with high visible transmittance is more beneficial for reducing the lighting energy but can lead to an increase in heat gain or loss.

In the second stage of the literature review, an energy simulation program was selected. Many programs have been reviewed and from them VisualDOE was selected because:

- It is widely verified for accuracy and consistency.
- VisualDOE simulates wide ranges of design features and energy conservation measures, including the integration of daylight with artificial lighting.
- Specifying building geometry is much faster in VisualDOE.
- VisualDOE implements daylight calculations.
- Its availability, sufficient training, and capability to maintain the program are further advantages.

For energy simulation program VisualDOE 4.1, many data input were required to formulate the base case office building. A survey was conducted among selected consultant offices to identify the main office building characteristics in the hot-humid climate represented by Dhahran. Despite many challenges during the survey, 12 A/E CO offices participated successfully. Based on the responses, the results can be considered as sufficiently accurate, given the participants' substantial experience. The results obtained from the survey were sufficient to create a base case model with the assistance of available architectural and lighting standards. The survey results showed that A/E CO considered the utilization of natural lighting in their design, but they apply no scientific method to design windows, and they rely on their experience to predict the amount of daylight entering the built space. On the other hand, the survey participants recommended the use of a lighting control strategy in order to integrate daylight with artificial lighting.

Based on the survey results, available standards and logical judgment for input data, a base case model was formulated. This base case is a square building with a dimension of $22\times22$ $m^2$ and 10 floors. It consists of four perimeter zones and an internal zone, and two lighting sensors were located in each perimeter zone to control the artificial lighting when there is sufficient natural lighting.

Once the base case model inputs were verified, simulations were conducted and the results, including building energy performance, were analyzed for comparison with available data for similar office buildings in the literature. The impact of daylight integration with artificial lighting on the base case model was investigated. The results showed that a reduction of about 35% of the lighting energy consumption can be achieved and a 13% reduction from the total energy consumption was obtained. Another advantage obtainable from the integration of daylight is the reduction in building cooling load. The results showed that there is a reduction in peak cooling load, and this reduction depends on the zone orientation. For example, in the north zone it is almost 10%, and in the south about 8%. A total reduction in building peak cooling load of 11% can be achieved when natural lighting is utilized.

An investigation was conducted on the impact of four types of glazing on the building energy performance. The results showed a significant reduction in lighting energy consumption regardless of the glazing type. The higher the visible transmittance of the glazing type, the lower the lighting energy consumption. On the other hand, the shading coefficient value of a glazing type was found to be the main factor that influences the total energy consumption and resulting energy savings when a particular window is used. Lower total energy consumption can be obtained at a lower shading coefficient value. Energy savings resulting from the daylight integration are maximized with a higher visible lighting transmittance and a lower shading coefficient of the selected glazing type.

The impact of various window heights on the energy performance of an office building was investigated. Results showed that window height affects energy savings due to lighting integration. Lower lighting energy consumption is obtained when a window height is increased, and this is due to the increase in the daylight transmitted into the built space.

A typical office building with specific geometrical configuration, and average floor area acquired from the survey, were utilized for the main findings in this research. The impact of the increase in the average floor area on an office building's energy performance was examined. The results demonstrated that the increase in the floor area makes no clear difference to either the reduction in lighting energy consumption or the total energy savings. This is only when the building's geometrical shape and perimeter zone depth are maintained as specified in the base case model. It can be concluded that this study is applicable for different floor areas, as the main indicator is the energy savings resulting from the daylight integration with artificial lighting.

Climatic conditions have major influences on the energy savings resulting from the integration of daylight with artificial lighting. The investigation compared the weather conditions of Jeddah and Riyadh, as they represent hot climates. The acquired results have shown similar energy savings for various window areas, as they have similar trends, but there is an almost constant difference in the energy savings. Consequently, results for Dhahran can be used for Riyadh and Jeddah.

A design tool was developed to assist in the energy-efficient integration of daylighting with artificial lighting for different window area, height, glazing type, and principal zone orientations. This design tool was presented in two ways. First, a set of the resulting energy savings graphs were presented, and each four graphs were grouped together for a specific window height and the principal zone orientations. These graphs can be used to identify the resulted energy savings from the daylight integration and to select the best window design to achieve the maximum energy savings. A number of examples were given and explained. Second, a set of four tables were developed to show the expected energy savings for a principal zone orientation, different window heights, and various glazing types. These tables can be used either to find the expected energy savings for a specific window design or to identify the ideal window design at which there are the highest energy savings. Several examples were given to explain how these tables are used.

## 5.2 Recommendations

Based on this study, the following design recommendations are offered to achieve energy-efficient integration of daylighting with artificial lighting and to utilize natural lighting efficiently in office buildings in hot humid climates.

1) The utilization of daylight is recommended at the early stage of building design, and available scientific methods and tools should be applied to predict and estimate daylight in office buildings.
2) To integrate daylight with artificial lighting, lighting control strategy should be installed in office buildings, and dimming control is recommended as it provides a more flexible response to changes in lighting conditions.
3) A large window area (WWR) is recommended in the north zone, whereas a smaller window area (WWR) is recommended for the other zones unless shading devices are installed to control the direct solar heat gain.
4) Increasing the window height is recommended, as this increases daylight penetration and reduces lighting energy consumption.
5) Double-glazed clear low-e should be installed in the north façade, as it provides the maximum energy savings.

6) In the remaining zone orientations, double-glazed clear low-e is recommended at small window areas, whereas at larger window areas double-glazed clear glass with heat-mirror is the best choice.
7) The utilization of the developing design assistant tool is recommended to help in energy-efficient window design through the integration of daylight and artificial lighting.
8) It is recommended to include the integration of daylight with artificial lighting in the Saudi Energy Code.

## 5.3 Recommendation for further research

This study has highlighted many findings that lead to future potential research. Different building geometries should be investigated to address the change from the square shape. In addition, shading devices can also be investigated for different orientations to reach an ideal window design for office buildings, especially in the east, south and west zones, so that large window areas can be specified. This study can be extended to address other building types, such as institutional and educational buildings, as lighting conditions are a major concern there. Furthermore, other glazing types and different window configurations can be investigated.

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# APPENDICES

## APPENDIX A: Data Collection Form

**OFFICE BUILDINGS DESIGN PRACTICE SURVEY IN SAUDI ARABIA**

**TO DESIGN OFFICE MANAGER**

**SUBJECT: SURVEY FOR THESIS RESEARCH**

Dear Sir,

Mr. Nagib Al-Ashwal is a Graduate student in the Architectural Engineering Department. He is currently collecting data for his Master thesis titled "***Energy-Efficient Window Design through the Integration of Daylighting and Artificial Lighting in Office Buildings*".** He is carrying out a survey to collect information regarding the building design parameters commonly used for office buildings in Saudi Arabia. Please distribute the questionnaire to the appropriate persons in your design office (e.g. Architects, Architectural Engineers, Construction Documents Developers or Specification Writers).

I hope that you will extend any assistance you can to make his research successful. We always value your participation and appreciate your active contribution in this phase of the study.

Thanks in advance for your positive cooperation.

Dr. Ismail Budaiwi
Thesis Supervisor,
Architectural Engineering Department

# Questionnaire Survey

This survey aims to gain information regarding office building design practice in the local market (Saudi Arabia). This information will be utilized in a scientific study which addresses energy efficient window design in office buildings where daylight is integrated with artificial lighting. Therefore, your participation will be highly beneficial to accomplish this research work.

**INSTRUCTIONS:** Please mark the answer that most closely reflects your design practice. (Respondent's information will remain anonymous, and data will be used for educational purposes only).

| ***Section I: Respondent's General Information*** | |
|---|---|
| **Name (Optional)** | |
| **Consultant office Name:** | |
| **Job Title:** | |

| 1. How many years of experience does your design office have in designing office buildings in Saudi Arabia? | | | |
|---|---|---|---|
| a. less than 5 years | ☐ | b. 10-15 years | ☐ |
| c. 5-10 years | ☐ | d. Over 15 years | ☐ |
| 2. What is the average number of office buildings that your design office has designed up-to-date? | | Number of Office Buildings =………….. | |

| ***Section II: Building General Information*** | | | |
|---|---|---|---|
| 1. What is the **common geometrical shape** that you normally use for an office building? | | 2. How many **floors** do you normally design for an office building? | |
| a. Square Shape | ☐ | a. <4 Floors | ☐ |
| b. Rectangular | ☐ | b. 4-10 Floors | ☐ |
| c. Irregular | ☐ | c. >10 Floors | ☐ |
| 3. On average, what is the floor area of an office building according to your design practice? | | 4. What type of **air-conditioning system** is normally used when you design office buildings? | |
| Floor Area=………..$m^2$ | | a. Packaged System | ☐ |
| | | b. Constant Volume Reheat Fan System | ☐ |
| | | c. Variable Air Volume System | ☐ |
| | | Others, please specify: ………………………. | |

## Section III: Building Envelope Design

| 1. What **exterior wall system** do you normally use for office buildings? | | 2. What type of **Building Material** do you normally use for Exterior Walls? | |
|---|---|---|---|
| a. Single Leaf wall | ☐ | a. CMU Blocks | ☐ |
| b. Sandwich Panel Wall | ☐ | b. Stone | ☐ |
| c. Double Leaf Wall | ☐ | c. Pre-Cast Concrete | ☐ |
| Others, please specify: ……………………… | | Others, please specify: ……………………… | |
| 3. What kind of **Exterior Finishing** do you normally use for Walls? | | 4. What **roof system** do you normally use for office buildings? | |
| a. Curtain Walls | ☐ | a. Reinforced Concrete Slab | ☐ |
| b. Pre-cast Concrete Panels | ☐ | b. Pre-cast Hollow-core Concrete Planks | ☐ |
| c. Stone Veneer | ☐ | c. Hordi Block Slab | ☐ |
| Others, please specify: …………………………… | | Others, please specify: ……………………… | |

| 5. According to your design practice, do you consider including thermal insulation to the wall and roof systems? | **Yes** ☐ | **No** ☐ |
|---|---|---|

| 6. If yes, what type of thermal insulation material is normally used? | | | |
|---|---|---|---|
| a. Fiber glass | ☐ | d. Rock wool | ☐ |
| b. Extruded polystyrene (XPS) | ☐ | e. Polyurethane | ☐ |
| c. Polyethylene | ☐ | Others, please specify: …………………… | |

| | |
|---|---|
| 7. Minimum R-value required for insulation material in **Wall Design** | ………… $m^2.°C / W$ |
| 8. Minimum R-value required for insulation material in **Roof Design** | ………… $m^2.°C / W$ |

## Window Designs

| 1. What **Glazing Types** or Components do you normally use: *(select one or more)* | | | |
|---|---|---|---|
| 1. Single-glazed layer: | | 2. Double-glazed layers: | |
| Clear | ☐ | a. Clear | ☐ |
| Bronze/Gray/Green Tint | ☐ | b. Bronze/Gray/Green Tint | ☐ |
| 3. Triple-glazed layers: | | c. Low-e with High-Solar-Gain | ☐ |
| a. Clear | ☐ | d. Low-e with Moderate-Solar-Gain | ☐ |
| b. Low-e | ☐ | e. Low-e with Low-Solar-Gain | ☐ |
| 4. Others, Please specify: ……………………………………………………………... | | | |

| 2. What **Window-to-Wall Ratio (WWR)** do you normally use in your design for different orientations? | | | |
|---|---|---|---|
| North: | WWR = ……………… | South: | WWR = ……………… |
| East: | WWR = ……………… | West: | WWR = ……………… |

## *Section IV: Lighting Design Requirements*

| | |
|---|---|
| 1. What is the illumination level you consider when designing for lighting in office buildings? | |
| ………... .. Lux (lm/$m^2$) | |
| 2. What is the Lighting Power Density (LPD) you normally consider when designing for lighting in office buildings? | |
| …………… W/$m^2$ | |
| 3. What type of lighting sources do you normally recommend for office buildings? | |
| a. Fluorescent lamps | ☐ |
| b. Incandescent lamps | ☐ |
| c. High Intensity Discharge Lamps | ☐ |
| Other, please specify: ……………………… | |
| 4. Do you consider the utilization of daylight when designing the lighting system for office buildings? | |
| *Yes* ☐ | *No* ☐ |

| | |
|---|---|
| 6. For what purpose is daylighting integrated with artificial lighting system? | |
| a. Enhance the visual environment | ☐ |
| b. Providing view to outside | ☐ |
| c. Energy conservation | ☐ |
| Other, please specify: ……………………… | |
| 7. What kind of **daylight prediction tools** do you use to estimate daylighting during schematic design? | |
| a. None | ☐ |
| b. Roles of thumb | ☐ |
| c. Experience from previous work | ☐ |
| d. Manual calculation Methods | ☐ |
| Other, please specify: ……………………… | |
| 8. What type of lighting control strategy do you normally recommend to integrate daylight with artificial lighting in office buildings? | |
| a. None | ☐ |
| b. Dimming | ☐ |
| c. Off/On | ☐ |
| d. Partially Off/On | ☐ |
| Other, please specify: ……………………… | |

| Please add any additional information that you think is important: |
|---|
| |
| |
| |
| |
| |
| |

## APPENDIX B: Sample of VisualDOE Input & Output Files

## Project Information

Name: Office Building
Address: KFUPM
Description: DEFAULT SI UNIT TEMPLATE
Analysis done by: Nageeb @ King Fahd University of Petroleum & Minerals
Gross Area: 4,840 m²
Conditioned Area: 4,840 m²
Project File: c:\program files\gdt4\shared\thesiswork\bc_22_10f.gph
Case Name: Copy of Base Case-Dctrl
Case Description: Copy based on Copy based on Base Case
Number of Blocks: 1

**Block 1, Level 1: Block_6**

| Block Information | |
|---|---|
| Shape | Rect |
| Zoning | Perimeter Interior |
| Zone Depth | 7 m |
| Number of Zones | 5 |
| Number of Facades | 4 |

| Ceiling and Plenum Heights | |
|---|---|
| Floor to Floor Height | 4.3 m |
| Plenum Height | 0.7 m |
| Number of Floors | 10 |

**Block Dimensions**

| Coordinates (m) | | Widths (m) | | Depths (m) | |
|---|---|---|---|---|---|
| X | 0 | Width | 22 | Depth | 22 |
| Y | 0 | | | | |
| Z | 0 | | | | |

**Block Constructions**

| Construction | Description | U-Factor (W/m²-°C) | HC (kJ/m²-K) |
|---|---|---|---|
| Roof | KSA OFF ROOF | 0.494 | 356.7 |
| Ceiling | Suspended Ceiling | 2.778 | 4.9 |
| Floor | KSA FLOOR | 0.514 | 752.9 |
| Int. Floor | KSA INT FLOOR | 0.974 | 286.2 |
| Interior Wall | Partition | 2.196 | 21.3 |

**Facade Dimensions**

| Name | Bay Width (m) | Window Height (m) | Window Width (m) |
|---|---|---|---|
| STH | Custom | n.a. | n.a. |
| WST | Custom | n.a. | n.a. |
| NTH | Custom | n.a. | n.a. |
| EST | Custom | n.a. | n.a. |

**Facade Shading**

| Name | Window Recess (m) | Interior Shading | Exterior Shading | Overhang Distance (m) | Overhang Projection (m) | Side Fin Distance (m) | Side Fin Projection (m) |
|---|---|---|---|---|---|---|---|
| STH | 0 | No | No | n.a. | n.a. | n.a. | n.a. |
| WST | 0 | No | No | n.a. | n.a. | n.a. | n.a. |
| NTH | 0 | No | No | n.a. | n.a. | n.a. | n.a. |
| EST | 0 | No | No | n.a. | n.a. | n.a. | n.a. |

**Facade Constructions**

| Name | Window Construction | U-Factor (W/m²-°C) | SC | VLT | Wall Construction | U-Factor (W/m²-°C) | HC (kJ/m²-K) |
|---|---|---|---|---|---|---|---|
| STH | customized | n.a. | n.a. | n.a. | KSA OFF | 0.535 | 256.2 |
| WST | customized | n.a. | n.a. | n.a. | KSA OFF | 0.535 | 256.2 |
| NTH | customized | n.a. | n.a. | n.a. | KSA OFF | 0.535 | 256.2 |
| EST | customized | n.a. | n.a. | n.a. | KSA OFF | 0.535 | 256.2 |

## Project Information

Name: Office Building
Address: KFUPM
Description: DEFAULT SI UNIT TEMPLATE
Analysis done by: Nageeb @ King Fahd University of Petroleum & Minerals
Project File: c:\program files\gdt4\shared\thesiswork\bc_22_10f.gph
Case Name: Copy of Base Case-Dctrl
Case Description: Copy based on Copy based on Base Case
Gross Area: 4,840 m²
Conditioned Area: 4,840 m²
Window-Wall-Ratio: 19.5%
Skylight-Roof-Ratio: 0.0%
Number of Blocks: 1
Note: This report includes floor multipliers

### Occupancies Summary

| Name | Area (m²) | Avg. LPD (W/m²) | Avg. EPD (W/m²) |
|---|---|---|---|
| KSA Office | 4,840 | 22.0 | 15.0 |
| Building Totals & Averages | 4,840 | 22.0 | 15.0 |

### Constructions Summary

| Name | Net Area (m²) | U-Factor (W/m²-°C) | HC (kJ/m²-°C) | Absorptance | Type | Category | Layers |
|---|---|---|---|---|---|---|---|
| KSA FLOOR | 484 | 0.51 | 752.89 | 0.0 | Floors | All | 4 |
| Partition | 2,578 | 2.19 | 21.3 | 0.3 | Partitions | Light | 3 |
| KSA OFF WALL | 2,429 | 0.53 | 256.18 | 0.5 | Walls | Light | 4 |
| KSA INT FLOOR | 4,840 | 0.97 | 286.17 | 0.5 | Floors | Light | 3 |

### Fenestrations Summary

| Name | Ucog (W/m²-°C) | SHGC | Tvis | North (m²) | East (m²) | South (m²) | West (m²) | Total (m²) | No. |
|---|---|---|---|---|---|---|---|---|---|
| 20% WWR | 2.741 | 0.698 | 0.781 | 0 | 0 | 0 | 158 | 158 | 10 |
| 40% WWR | 2.741 | 0.698 | 0.781 | 264 | 0 | 0 | 0 | 264 | 10 |
| 25% WWR | 2.741 | 0.698 | 0.781 | 0 | 0 | 198 | 0 | 198 | 10 |
| 15% WWR | 2.741 | 0.698 | 0.781 | 0 | 119 | 0 | 0 | 119 | 10 |
| Building Totals & Averages | 2.741 | 0.698 | 0.781 | 264 | 119 | 198 | 158 | 739 | 40 |

**Project Information**
Name: Office Building
Address: KFUPM
Description: DEFAULT SI UNIT TEMPLATE
Analysis done by: Nageeb @ King Fahd University of Petroleum & Minerals
Project File: c:\program files\gdt4\shared\thesiswork\bc_22_10f.gph
Case Name: Copy of Base Case-Dctrl
Case Description: Copy based on Copy based on Base Case
Number of Blocks: 1

**Zone Loads**

| Name | Area (m²) | LPD (W/m²) | EPD (W/m²) | Occupancy | Occupant Density (m²/perso | Daylight Control | Illuminance (lux) | Control Fraction | Infiltration (ach) | SS-G Max Cl/Ht |
|---|---|---|---|---|---|---|---|---|---|---|
| SOUTH | 1050 | 21.997 | 15.00 | KSA Office | 15.0 | Dimming | 500, 500 | 0.5, 0.3 | 0.5 | n.a./n.a. |
| WEST | 1050 | 21.997 | 15.00 | KSA Office | 15.0 | Dimming | 500, 500 | 0.5, 0.3 | 0.5 | n.a./n.a. |
| NORTH | 1050 | 21.997 | 15.00 | KSA Office | 15.0 | Dimming | 500, 500 | 0.5, 0.3 | 0.5 | n.a./n.a. |
| EAST | 1050 | 21.997 | 15.00 | KSA Office | 15.0 | Dimming | 500, 500 | 0.5, 0.3 | 0.5 | n.a./n.a. |
| INTERIOR | 640 | 21.997 | 15.00 | KSA Office | 15.0 | None | n.a. | n.a. | 0.5 | n.a./n.a. |

**Supply Air**

| Name | Total Flow (l/s) | Flow/Area (l/s/(m²)) | Air change/hour | Min. Flow Ratio | Cool/Heat Cap. (kW) |
|---|---|---|---|---|---|
| SOUTH | AutoSized - 936.1111 | 0 | 0 | 1 | n.a. |
| WEST | AutoSized - 673.8889 | 0 | 0 | 1 | n.a. |
| NORTH | AutoSized - 666.1111 | 0 | 0 | 1 | n.a. |
| EAST | AutoSized - | 0 | 0 | 1 | n.a. |
| INTERIOR | AutoSized - 311.6667 | 0 | 0 | 1 | n.a. |

**Outside Air**

| Name | Total Flow (l/s) | Flow(cfm)/Person | Air | Fraction Supply Air |
|---|---|---|---|---|
| SOUTH | n.a. | 10 | n.a. | n.a. |
| WEST | n.a. | 10 | n.a. | n.a. |
| NORTH | n.a. | 10 | n.a. | n.a. |
| EAST | n.a. | 10 | n.a. | n.a. |
| INTERIOR | n.a. | 10 | n.a. | n.a. |

| | **Thermostat** | | **PIU** | | |
|---|---|---|---|---|---|
| Name | Type | Throttling Range (°C) | Type | Zone Fan Volume (l/s) | Fan Power (W) |
| SOUTH | Reverse Action | 2 | No PIU | n.a. | n.a. |
| WEST | Reverse Action | 2 | No PIU | n.a. | n.a. |
| NORTH | Reverse Action | 2 | No PIU | n.a. | n.a. |
| EAST | Reverse Action | 2 | No PIU | n.a. | n.a. |
| INTERIOR | Reverse Action | 2 | No PIU | n.a. | n.a. |

| | **Zone Reheat** | | **Baseboards** | |
|---|---|---|---|---|
| Name | Reheat Delta-T (°C) | Heat Source | Rating (kW) | Control |

---------------------------------------------------------------------------------------------------------------------------------

NUMBER OF WINDOWS 4 RECTANGULAR 4 OTHER 0

RECTANGULAR WINDOWS (U-VALUES INCLUDE OUTSIDE AIR FILM(

| WINDOW NAME | MULTIPLIER | GLASS AREA ( M2 ) | GLASS HEIGHT ( M) | GLASS WIDTH ( M) | LOCATION OF ORIGIN IN SURFACE COORDINATES X ( M) | Y ( M) | FRAME AREA ( M2 ) | FRAME U-VALUE (W/M2-K( |
|---|---|---|---|---|---|---|---|---|
| Window11084 | 1.0 | 19.80 | 1.20 | 16.50 | 2.80 | 1.00 | 0.00 | 0.428 |
| Window11085 | 1.0 | 15.84 | 1.20 | 13.20 | 4.40 | 1.00 | 0.00 | 0.428 |
| Window11083 | 1.0 | 26.40 | 1.20 | 22.00 | 0.00 | 1.00 | 0.00 | 0.428 |
| Window11081 | 1.0 | 11.88 | 1.20 | 9.90 | 6.10 | 1.00 | 0.00 | 0.428 |

| WINDOW NAME | SETBACK ( M) | X-DIVISIONS | GLASS SHADING COEFF | NUMBER OF PANES | GLASS TYPE CODE | INFILTRATION FLOW COEFF | CENTER-OF-GLASS U-VALUE (W/M2-K ) | GLASS VISIBLE TRANS |
|---|---|---|---|---|---|---|---|---|
| Window11084 | 0.00 | 10 | 0.81 | 2 | 2004 | 0.0 | 2.791 | 0.781 |
| Window11085 | 0.00 | 10 | 0.57 | 2 | 2203 | 0.0 | 3.216 | 0.473 |
| Window11083 | 0.00 | 10 | 0.81 | 2 | 2004 | 0.0 | 2.791 | 0.781 |
| Window11081 | 0.00 | 10 | 0.81 | 2 | 2004 | 0.0 | 2.791 | 0.781 |

```
1Green Design Tools                                                                DOE-2.1E-119  Mon May 12 04:45:49 2008LDL RUN
1
 Copy of Base Case-Dctrl                 DT4\Shared\ThesisWork\BC_22_10F.gph     VisualDOE 4.1.2
 REPORT- LS-C BUILDING PEAK LOAD COMPONENTS                                                 WEATHER FILE- DHAHRAN SAUDI ARABIA
-------------------------------------------------------------------------------------------------------------------------------
---
 *** BUILDING***
                     FLOOR  AREA     52097  SQFT      4840   M2
                     VOLUME         734970  CUFT     20814   M3


                                           COOLING  LOAD                                HEATING  LOAD
==========================                ==========================
     TIME                                    SEP 26  4PM

     DRY-BULB TEMP                       103 F            39 C
     WET-BULB TEMP                        71 F            22 C
     TOT HORIZONTAL SOLAR RAD            176 BTU/H.SQFT   554 W/M2
     WINDSPEED AT SPACE                  3.0 KTS          1.5 M/S
     CLOUD AMOUNT 0(CLEAR)-10              0

                                 SENSIBLE         LATENT                                  SENSIBLE
)                              KBTU/H)    ( KW )  (KBTU/H)  ( KW )                    (KBTU/H)  ( KW  (
--------  --------                      ------  --------  ------    --------

      WALL CONDUCTION          77.103    22.591     0.000   0.000                        0.000     0.000
      ROOF CONDUCTION           0.000     0.000     0.000   0.000                        0.000     0.000
      WINDOW GLASS+FRM COND   174.770    51.208     0.000   0.000                        0.000     0.000
      WINDOW GLASS SOLAR      195.729    57.349     0.000   0.000                        0.000     0.000
      DOOR CONDUCTION           0.000     0.000     0.000   0.000                        0.000     0.000
      INTERNAL SURFACE COND   272.665    79.891     0.000   0.000                        0.000     0.000
      UNDERGROUND SURF COND     0.000     0.000     0.000   0.000                        0.000     0.000
      OCCUPANTS TO SPACE       64.324    18.847    61.670  18.069                        0.000     0.000
      LIGHT     TO SPACE      302.544    88.645     0.000   0.000                        0.000     0.000
      EQUIPMENT TO SPACE      223.172    65.389     0.000   0.000                        0.000     0.000
      PROCESS   TO SPACE        0.000     0.000     0.000   0.000                        0.000     0.000
      INFILTRATION              0.000     0.000     0.000   0.000                        0.000     0.000
--------  --------                      ------  -------   -------   --------
      TOTAL                  1310.307   383.920    61.670  18.069                        0.000     0.000
      TOTAL / AREA              0.025     0.079     0.001   0.004                        0.000     0.000
```

| | | | | | |
|---|---|---|---|---|---|
| TOTAL LOAD | 1371.977 KBTU/H | 401.989 KW | | 0.000 KBTU/H | 0.000 KW |
| TOTAL LOAD / AREA | 26.33 BTU/H.SQFT | 83.056 W/M2 | | 0.000 BTU/H.SQFT | 0.000 W/M2 |

Green Design Tools DOE-2.1E-119 Mon May 12 04:45:49 2008LDL RUN 1

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REPORT- LS-D BUILDING MONTHLY LOADS SUMMARY WEATHER FILE- DHAHRAN SAUDI ARABIA

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| | - - - - - - - - C O O L I N G - - - - - - - - | | | | | | - - - - - - - - H E A T I N G - - - - - - - - | | | | | | - - - E L E C - - - | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| MONTH | COOLING ENERGY ( MWH) | TIME OF MAX DY | HR | DRY-BULB TEMP | WET-BULB TEMP | MAXIMUM COOLING LOAD (KW ) | HEATING ENERGY ( MWH) | TIME OF MAX DY | HR | DRY-BULB TEMP | WET-BULB TEMP | MAXIMUM HEATING LOAD (KW ) | ELEC-TRICAL ENERGY (KWH) | MAXIMUM ELEC LOAD (KW( |
| JAN | 126.19452 | 23 | 15 | 21.C | 14.C | 338.360 | 0.000 | | | | | 0.000 | 53507. | 179.065 |
| FEB | 109.38525 | 8 | 15 | 24.C | 13.C | 349.804 | 0.000 | | | | | 0.000 | 38394. | 179.065 |
| MAR | 142.14250 | 27 | 15 | 32.C | 25.C | 352.187 | 0.000 | | | | | 0.000 | 50390. | 179.065 |
| APR | 147.21388 | 29 | 15 | 39.C | 23.C | 356.082 | 0.000 | | | | | 0.000 | 49118. | 179.065 |
| MAY | 174.27107 | 28 | 15 | 41.C | 22.C | 362.784 | 0.000 | | | | | 0.000 | 49663. | 179.065 |
| JUN | 174.79074 | 19 | 10 | 41.C | 22.C | 347.306 | 0.000 | | | | | 0.000 | 44994. | 150.460 |
| JUL | 187.10097 | 19 | 11 | 44.C | 24.C | 359.005 | 0.000 | | | | | 0.000 | 48571. | 147.211 |

```
 AUG    183.42365    5  15   45.C  24.C       372.820          0.000                               0.000        48993.
179.065

 SEP    172.28816   26  15   39.C  22.C       383.920          0.000                               0.000        47595.
179.065

 OCT    169.32466   11  12   39.C  22.C       354.677          0.000                               0.000        48923.
141.465

 NOV    140.04820   12  16   28.C  24.C       337.997          0.000                               0.000        47368.
179.065

 DEC    125.34283   20  15   24.C  18.C       342.101          0.000                               0.000        45274.
179.065
-----    --------      ----------                         ---------      ----------                          ---------
--

 TOTAL   1851.526                                          0.000                                           572791.

 MAX                                      383.920                                              0.000
179.065


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 REPORT- LS-G  SPACE DAYLIGHTING SUMMARY                                                   WEATHER FILE- DHAHRAN SAUDI ARABIA
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---

 SPACE  SOUTH_C
-----------------                                                              REPORT SCHEDULE HOURS WITH SUN UP---------------
-
              PERCENT LIGHTING          PERCENT LIGHTING            AVERAGE     PERCENT HOURS
              ENERGY REDUCTION          ENERGY REDUCTION           DAYLIGHT         DAYLIGHT
                BY DAYLIGHTING            BY DAYLIGHTING        ILLUMINANCE       ILLUMINANCE          AVERAGE    PERCENT
HOURS
)                  ALL HOURS)   (REPORT SCHEDULE HOURS)      ( LUX       )    ABOVE SETPOINT      GLARE INDEX   GLARE TOO
HIGH
```

| MONTH | TOTAL ZONE | REF PT 1 | REF PT 2 | TOTAL ZONE | REF PT 1 | REF PT 2 | REF PT 1 | REF PT 2 | REF PT 1 | REF PT 2 | REF PT 1 | REF PT 2 | REF PT 1 | REF PT 2 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| JAN | 34.1 | 43.2 | 41.5 | 34.1 | 43.2 | 41.5 | 2609.4 | 789.4 | 51.4 | 47.8 | 12.5 | 11.5 | 14.9 | 0.6 |
| FEB | 32.3 | 41.1 | 39.2 | 32.3 | 41.1 | 39.2 | 2309.4 | 636.3 | 50.0 | 48.8 | 12.4 | 11.3 | 21.4 | 0.9 |
| MAR | 35.6 | 44.8 | 44.1 | 35.6 | 44.8 | 44.1 | 1607.3 | 491.4 | 52.2 | 44.1 | 11.7 | 10.6 | 17.5 | 0.0 |
| APR | 43.6 | 55.7 | 52.3 | 43.6 | 55.7 | 52.3 | 1260.9 | 425.8 | 53.2 | 40.7 | 12.0 | 10.8 | 12.7 | 0.0 |
| MAY | 46.9 | 59.5 | 56.9 | 46.9 | 59.5 | 56.9 | 980.5 | 356.2 | 53.5 | 39.0 | 11.5 | 10.5 | 10.8 | 0.0 |
| JUN | 49.5 | 63.6 | 59.0 | 49.5 | 63.6 | 59.0 | 899.6 | 344.3 | 58.9 | 35.3 | 12.4 | 11.1 | 10.9 | 0.0 |
| JUL | 50.5 | 64.5 | 60.9 | 50.5 | 64.5 | 60.9 | 993.5 | 373.3 | 55.7 | 36.1 | 12.4 | 11.1 | 13.6 | 0.0 |
| AUG | 45.5 | 57.2 | 56.4 | 45.5 | 57.2 | 56.4 | 1256.4 | 439.2 | 57.7 | 43.5 | 11.8 | 10.6 | 19.3 | 0.0 |
| SEP | 39.1 | 49.0 | 48.7 | 39.1 | 49.0 | 48.7 | 1679.4 | 527.3 | 54.9 | 47.9 | 12.0 | 10.9 | 15.9 | 0.0 |
| OCT | 52.5 | 65.8 | 65.3 | 52.5 | 65.8 | 65.3 | 2553.7 | 824.5 | 77.2 | 63.8 | 16.7 | 14.0 | 30.1 | 1.5 |
| NOV | 48.2 | 61.2 | 58.8 | 48.2 | 61.2 | 58.8 | 3193.7 | 1013.7 | 72.4 | 68.3 | 16.6 | 14.0 | 29.9 | 0.3 |
| DEC | 37.9 | 47.9 | 46.6 | 37.9 | 47.9 | 46.6 | 3122.3 | 1046.1 | 63.6 | 61.0 | 13.0 | 11.9 | 19.1 | 0.0 |

```
-----  ------   ------  ------   ------  ------    ------  ------     ------  ------  -----     ------  ------  -----
-

 ANNUAL    43.4    55.0    53.0      43.4    55.0    53.0     1795.0   584.2      58.2    47.2     12.8    11.5     17.6
0.3

1Green Design Tools                                                                DOE-2.1E-119  Mon May 12 04:45:49 2008LDL RUN
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 REPORT- LS-G  SPACE DAYLIGHTING SUMMARY                                                      WEATHER FILE- DHAHRAN SAUDI ARABIA
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 SPACE  WEST_C
-----------------                                                              REPORT SCHEDULE HOURS WITH SUN UP---------------
-

               PERCENT LIGHTING          PERCENT LIGHTING            AVERAGE     PERCENT HOURS
               ENERGY REDUCTION          ENERGY REDUCTION           DAYLIGHT        DAYLIGHT
                 BY DAYLIGHTING            BY DAYLIGHTING        ILLUMINANCE      ILLUMINANCE          AVERAGE    PERCENT
HOURS
)                    ALL HOURS)   (REPORT SCHEDULE HOURS)      ( LUX       )    ABOVE SETPOINT      GLARE INDEX   GLARE TOO
HIGH
-------------   -------------   -------------    -------------     ----------------------   --------------------
-
          TOTAL  REF PT  REF PT     TOTAL  REF PT  REF PT     REF PT  REF PT    REF PT  REF PT   REF PT  REF PT   REF PT  REF
PT
 MONTH     ZONE       1       2      ZONE       1       2          1       2         1       2        1       2        1
2
-----  ------   ------  ------   ------  ------    ------  ------     ------  ------  -----     ------  ------  -----    -----
-

 JAN       22.9    35.7    16.9      22.9    35.7    16.9      288.1   101.1      22.9     0.0     10.0     8.7      0.0
0.0

 FEB       24.5    37.2    19.5      24.5    37.2    19.5      329.9   117.2      31.2     0.0     10.1     9.0      0.0
0.0

 MAR       26.9    40.2    22.6      26.9    40.2    22.6      315.8   114.7      27.8     0.0      9.5     8.4      0.0
0.0

 APR       31.5    46.9    26.7      31.5    46.9    26.7      345.7   132.9      32.0     0.0      9.8     8.6      0.0
0.0
```

```
 MAY       38.0    56.1    33.1      38.0    56.1    33.1      372.7   142.3      40.3     0.0      9.7     8.6      0.0
0.0

 JUN       42.5    61.8    38.7      42.5    61.8    38.7      416.5   165.5      40.0     0.0     10.4     9.2      0.0
0.0

 JUL       43.5    62.9    40.1      43.5    62.9    40.1      432.5   170.6      41.4     0.0     10.4     9.2      0.0
0.0

 AUG       37.4    54.3    34.0      37.4    54.3    34.0      409.6   157.3      43.0     0.0     10.0     8.9      0.9
0.0

 SEP       30.5    45.5    26.0      30.5    45.5    26.0      362.3   133.7      35.4     0.0     10.0     8.9      0.0
0.0

 OCT       45.0    65.3    41.1      45.0    65.3    41.1      590.5   304.6      49.4     6.6     13.4    11.7      0.0
0.0

 NOV       38.6    57.6    32.7      38.6    57.6    32.7      459.0   202.3      45.2     3.5     13.0    11.2      0.0
0.0

 DEC       24.4    38.0    18.2      24.4    38.0    18.2      317.5   119.5      28.2     0.3     10.4     8.9      0.0
0.0
-----  ------   ------  ------   ------  ------    ------  ------     ------  ------  -----     ------  ------  -----
-

 ANNUAL    34.3    50.8    29.6      34.3    50.8    29.6      388.9   156.0      36.7     0.8     10.5     9.3      0.1
0.0

1Green Design Tools                                                                DOE-2.1E-119  Mon May 12 04:45:49 2008LDL RUN
1
 Copy of Base Case-Dctrl                DT4\Shared\ThesisWork\BC_22_10F.gph     VisualDOE 4.1.2
 REPORT- LS-G  SPACE DAYLIGHTING SUMMARY                                                       WEATHER FILE- DHAHRAN SAUDI ARABIA
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---
 SPACE  NORTH_C

-----------------                                                                REPORT SCHEDULE HOURS WITH SUN UP---------------
-

              PERCENT LIGHTING          PERCENT LIGHTING            AVERAGE     PERCENT HOURS
              ENERGY REDUCTION          ENERGY REDUCTION           DAYLIGHT          DAYLIGHT
                BY DAYLIGHTING            BY DAYLIGHTING        ILLUMINANCE       ILLUMINANCE          AVERAGE    PERCENT
HOURS
```

| ) | ALL HOURS) | | | (REPORT SCHEDULE HOURS) | | | ( LUX ) | | ABOVE SETPOINT | | GLARE INDEX | | GLARE TOO HIGH | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| MONTH | TOTAL ZONE | REF PT 1 | REF PT 2 | TOTAL ZONE | REF PT 1 | REF PT 2 | REF PT 1 | REF PT 2 | REF PT 1 | REF PT 2 | REF PT 1 | REF PT 2 | REF PT 1 | REF PT 2 |
| JAN | 29.6 | 39.8 | 32.4 | 29.6 | 39.8 | 32.4 | 536.3 | 215.1 | 39.8 | 17.7 | 11.5 | 10.4 | 8.0 | 0.0 |
| FEB | 30.4 | 39.8 | 35.2 | 30.4 | 39.8 | 35.2 | 729.6 | 265.5 | 41.7 | 25.3 | 12.3 | 10.8 | 22.3 | 0.0 |
| MAR | 34.3 | 44.3 | 40.4 | 34.3 | 44.3 | 40.4 | 932.2 | 300.9 | 47.1 | 27.1 | 12.4 | 10.6 | 20.0 | 0.3 |
| APR | 40.3 | 52.3 | 47.3 | 40.3 | 52.3 | 47.3 | 1238.8 | 375.1 | 49.2 | 33.7 | 13.1 | 11.2 | 21.0 | 3.5 |
| MAY | 46.4 | 59.3 | 55.9 | 46.4 | 59.3 | 55.9 | 1450.7 | 438.8 | 52.2 | 40.7 | 12.9 | 11.2 | 20.5 | 10.6 |
| JUN | 50.3 | 64.1 | 61.0 | 50.3 | 64.1 | 61.0 | 1603.0 | 495.0 | 60.0 | 40.0 | 13.9 | 12.1 | 20.0 | 13.1 |
| JUL | 50.7 | 64.6 | 61.5 | 50.7 | 64.6 | 61.5 | 1577.3 | 498.4 | 58.6 | 41.4 | 13.7 | 12.0 | 21.6 | 13.1 |
| AUG | 44.7 | 57.1 | 53.9 | 44.7 | 57.1 | 53.9 | 1418.9 | 446.0 | 50.5 | 42.6 | 12.9 | 11.0 | 22.6 | 7.7 |
| SEP | 37.9 | 48.4 | 45.8 | 37.9 | 48.4 | 45.8 | 1195.9 | 367.1 | 52.3 | 35.1 | 13.0 | 11.2 | 22.6 | 2.8 |
| OCT | 45.8 | 59.9 | 52.7 | 45.8 | 59.9 | 52.7 | 1001.6 | 371.7 | 58.0 | 32.2 | 15.9 | 13.5 | 15.9 | 0.0 |
| NOV | 40.4 | 53.3 | 46.0 | 40.4 | 53.3 | 46.0 | 752.5 | 304.8 | 54.8 | 29.0 | 14.9 | 13.1 | 17.6 | 0.0 |

```
 DEC        30.4    41.0    33.2      30.4    41.0    33.2      551.3   232.7      47.8    18.8     11.7    10.8      6.7
0.0
-----  ------   ------  ------   ------  ------    ------  ------     ------  ------  -----     ------  ------  -----
-

 ANNUAL     40.6    52.6    47.7      40.6    52.6    47.7     1119.1   368.3      51.4    32.7     13.2    11.5     18.5
4.7

1Green Design Tools                                                                      DOE-2.1E-119  Mon May 12 04:45:49 2008LDL RUN
1
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 REPORT- LS-G  SPACE DAYLIGHTING SUMMARY                                                                     WEATHER FILE- DHAHRAN SAUDI ARABIA
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 SPACE  EAST_C

-----------------                                                               REPORT SCHEDULE HOURS WITH SUN UP---------------
-

               PERCENT LIGHTING          PERCENT LIGHTING            AVERAGE     PERCENT HOURS
               ENERGY REDUCTION          ENERGY REDUCTION            DAYLIGHT         DAYLIGHT
                 BY DAYLIGHTING            BY DAYLIGHTING         ILLUMINANCE       ILLUMINANCE         AVERAGE    PERCENT
HOURS
)                    ALL HOURS)   (REPORT SCHEDULE HOURS)      ( LUX       )    ABOVE SETPOINT      GLARE INDEX   GLARE TOO
HIGH
-------------   --------------   --------------    --------------     -----------------------   ---------------------
-
          TOTAL  REF PT  REF PT     TOTAL  REF PT  REF PT     REF PT  REF PT    REF PT  REF PT   REF PT  REF PT   REF PT  REF
PT
 MONTH     ZONE       1       2      ZONE       1       2          1       2         1       2        1       2        1
2
-----  ------   ------  ------   ------  ------    ------  ------     ------  ------  -----     ------  ------  -----    -----
-

 JAN        30.7    40.1    35.6      30.7    40.1    35.6     2492.6  1730.5      46.4    37.6     13.4    11.2     30.1
25.1

 FEB        30.5    39.6    35.7      30.5    39.6    35.7     2642.8  1736.6      47.0    40.2     12.9    10.9     26.5
17.3

 MAR        34.3    44.3    40.4      34.3    44.3    40.4     2386.9  1468.4      47.6    39.7     12.3    10.4     21.3
18.0
```

```
 APR       39.0    50.9    45.3      39.0    50.9    45.3     2476.0  1523.6      49.5    41.0     12.4    10.4     19.5
13.5

 MAY       43.8    57.0    50.9      43.8    57.0    50.9     2493.8  1451.6      52.2    42.5     12.0    10.4     20.5
9.7

 JUN       46.0    60.2    53.0      46.0    60.2    53.0     2575.6  1451.7      53.3    45.6     12.7    10.8     20.0
6.2

 JUL       46.7    61.2    53.7      46.7    61.2    53.7     2581.4  1416.5      51.7    41.9     12.7    10.8     22.0
10.2

 AUG       42.2    54.8    49.3      42.2    54.8    49.3     2622.7  1474.5      50.5    43.3     12.1    10.4     25.6
14.4

 SEP       37.1    48.0    43.8      37.1    48.0    43.8     2780.4  1742.8      46.4    43.1     12.6    10.7     20.5
15.4

 OCT       42.9    57.3    47.3      42.9    57.3    47.3     2701.9  1574.0      54.9    46.6     15.5    12.9     22.8
19.7

 NOV       38.4    51.4    42.5      38.4    51.4    42.5     2914.3  1942.6      54.8    42.5     16.0    13.2     28.4
25.2

 DEC       30.7    40.3    35.2      30.7    40.3    35.2     2693.2  1914.2      49.0    41.3     14.4    11.9     36.4
27.0
-----  ------   ------  ------   ------  ------    ------  ------     ------  ------  -----     ------  ------  -----
-

 ANNUAL    38.9    51.0    44.8      38.9    51.0    44.8     2607.1  1602.0      50.4    42.2     13.2    11.1     24.1
16.2

1Green Design Tools                                                                DOE-2.1E-119  Mon May 12 04:45:49 2008PDL RUN
1
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 REPORT- PS-E  MONTHLY ENERGY END-USE SUMMARY                                                WEATHER FILE- DHAHRAN SAUDI ARABIA
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0ELECTRICAL END-USES IN KWH

                  JAN      FEB      MAR      APR      MAY      JUN      JUL      AUG      SEP      OCT      NOV      DEC
TOTAL
---  -------  -------  -------  -------  -------  -------  -------  -------  -------  -------  -------  -------
----
```

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0AREA LIGHTS | 22884. | 14175. | 20551. | 19584. | 19040. | 16244. | 17948. | 18762. | 18846. | 18301. | 18226. | 17396. | 221957. |
| MAX KW | 106.5 | 106.5 | 106.5 | 106.5 | 106.5 | 77.9 | 74.6 | 106.5 | 106.5 | 94.9 | 106.5 | 106.5 | 106.5 |
| DAY/HR | 1/14 | 1/14 | 1/14 | 1/15 | 1/16 | 26/16 | 22/16 | 1/16 | 2/15 | 25/ 8 | 4/16 | 10/15 | |
| 0MISC EQUIPMT | 30622. | 24219. | 29838. | 29533. | 30622. | 28749. | 30622. | 30230. | 28749. | 30622. | 29141. | 27878. | 350829. |
| MAX KW | 72.6 | 72.6 | 72.6 | 72.6 | 72.6 | 72.6 | 72.6 | 72.6 | 72.6 | 72.6 | 72.6 | 72.6 | 72.6 |
| DAY/HR | 1/ 9 | 1/ 9 | 1/ 9 | 1/ 9 | 1/ 9 | 3/ 9 | 1/ 9 | 1/ 9 | 2/ 9 | 1/ 9 | 1/ 9 | 10/ 9 | |
| 0SPACE COOL | 18416. | 11388. | 31239. | 39839. | 61945. | 65071. | 79465. | 78415. | 63418. | 63482. | 32551. | 16312. | 561540. |
| MAX KW | 97.0 | 96.7 | 171.7 | 208.4 | 209.1 | 228.1 | 243.8 | 249.9 | 236.0 | 221.7 | 158.3 | 148.2 | 249.9 |
| DAY/HR | 7/14 | 13/16 | 28/14 | 29/14 | 24/13 | 27/12 | 22/12 | 15/13 | 3/15 | 2/13 | 4/12 | 10/15 | |
| 0VENT FANS | 14916. | 8175. | 14198. | 14342. | 14916. | 13625. | 14916. | 14772. | 13195. | 14916. | 13768. | 10470. | 162207. |
| MAX KW | 35.9 | 35.9 | 35.9 | 35.9 | 35.9 | 35.9 | 35.9 | 35.9 | 35.9 | 35.9 | 35.9 | 35.9 | 35.9 |
| DAY/HR | 1/ 7 | 1/ 7 | 1/ 7 | 1/ 7 | 1/ 7 | 1/ 7 | 1/ 7 | 1/ 7 | 2/ 7 | 1/ 7 | 1/ 7 | 10/ 7 | |
| | ======= | ======= | ======= | ======= | ======= | ======= | ======= | ======= | ======= | ======= | ======= | ======= | ======== |
| 0TOTAL KWH | 86838. | 57957. | 95827. | 103299. | 126523. | 123690. | 142951. | 142179. | 124207. | 127321. | 93686. | 72056. | 1296533. |

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1Green Design Tools                                                                             DOE-2.1E-119  Mon May 12 04:45:49 2008PDL RUN
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 REPORT- BEPS  BUILDING ENERGY PERFORMANCE SUMMARY                                           WEATHER FILE- DHAHRAN SAUDI ARABIA
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                                   ENERGY TYPE:   ELECTRICITY   NATURAL-GAS
                                   UNITS:  MWH

                                CATEGORY OF USE
---------------

                                    AREA LIGHTS         222.0           0.0

                                   MISC EQUIPMT         350.8           0.0

                                     SPACE COOL         561.5           0.0

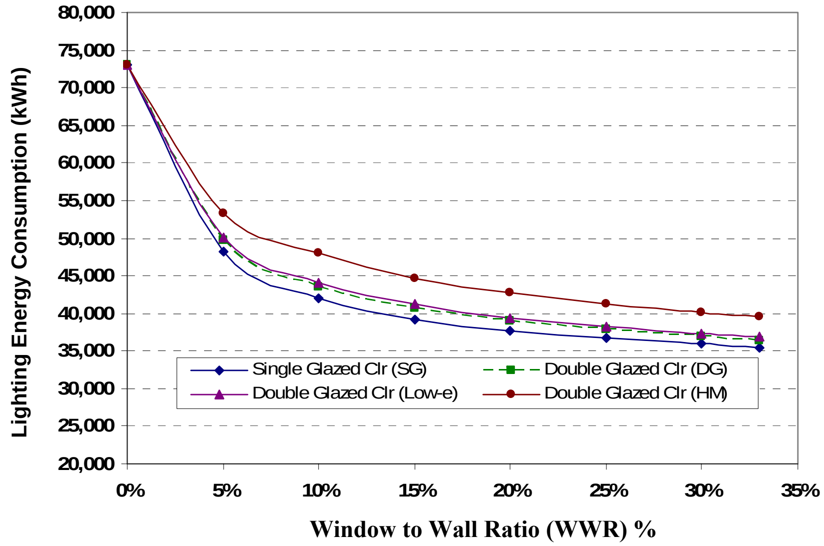
                                      VENT FANS         162.2           0.0

                                   DOMHOT WATER           0.0           0.0
----------    ----------

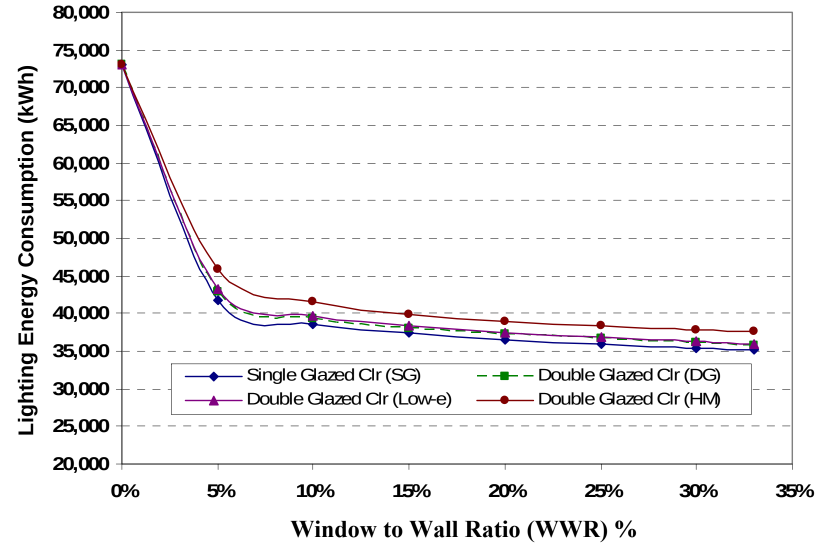
                                          TOTAL        1296.5           0.0


                    TOTAL SITE ENERGY      1296.52  MWH    267.8 KWH/M2-YR    GROSS-AREA    267.8 KWH/M2-YR    NET-AREA
                    TOTAL SOURCE ENERGY    3889.95  MWH    803.4 KWH/M2-YR    GROSS-AREA    803.4 KWH/M2-YR    NET-AREA
```

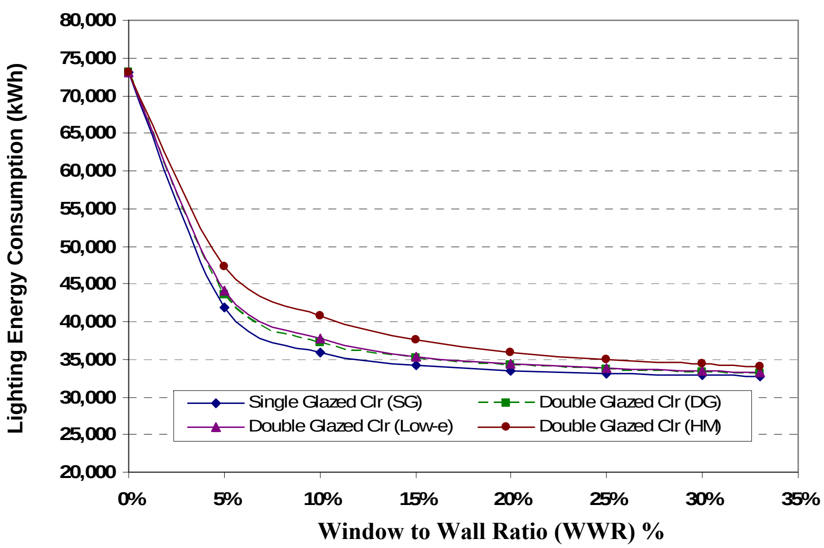
## APPENDIX C: Lighting Energy Consumption for Various Glazing Types – Various Window Heights – Principal Zone Orientations



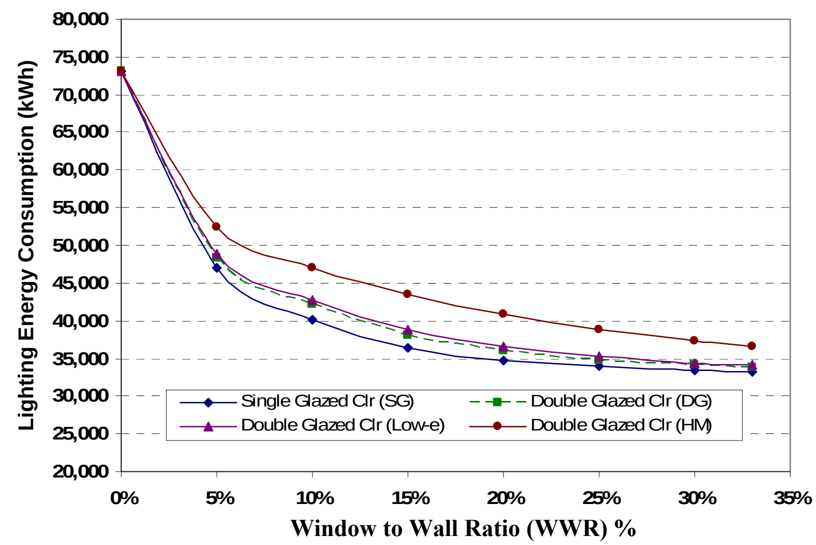

**Lighting energy consumption for various glazing types- 1.20m window height- North zone**



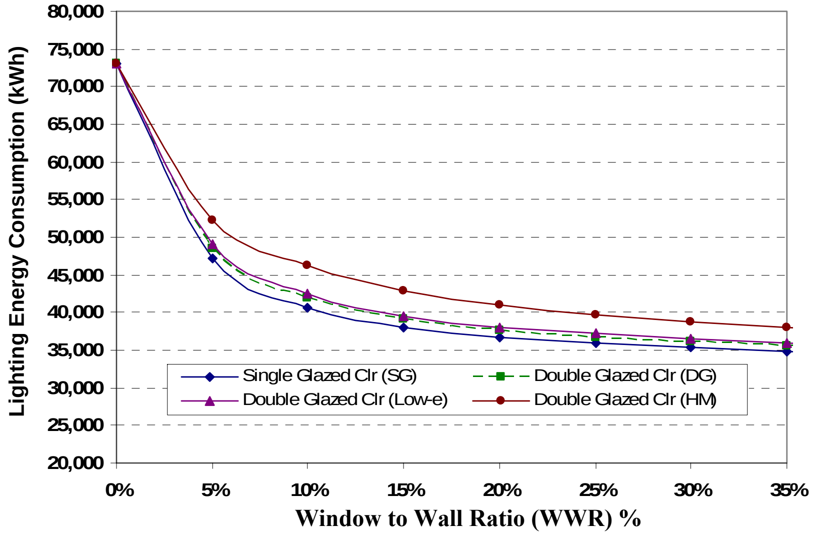

**Lighting energy consumption for various glazing types- 1.20m window height- East zone**



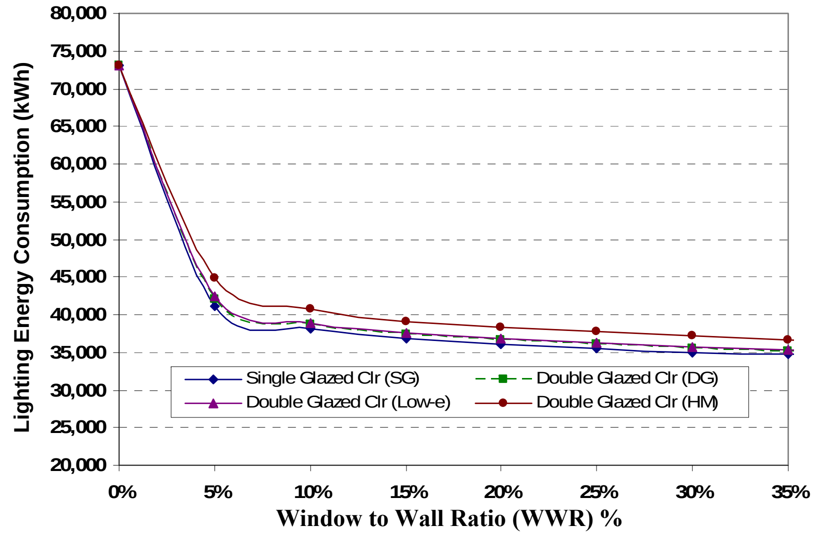

**Lighting energy consumption for various glazing types- 1.20m window height- South zone**



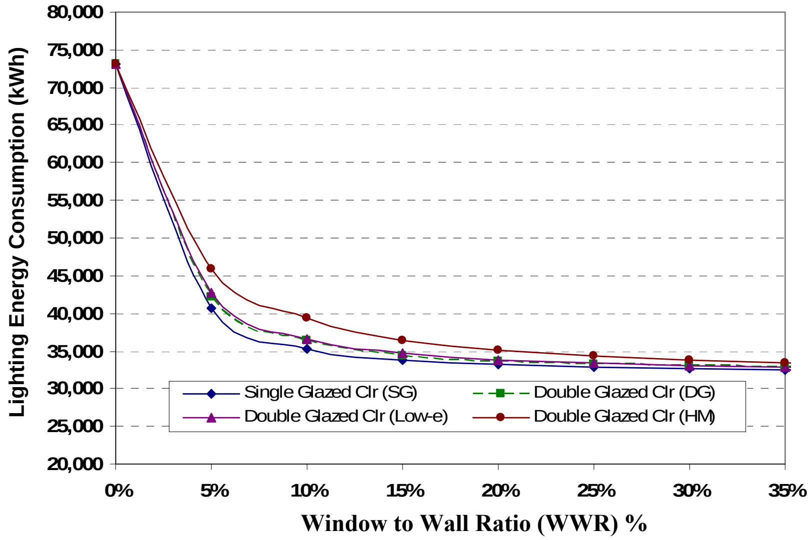

**Lighting energy consumption for various glazing types- 1.20m window height- West zone**



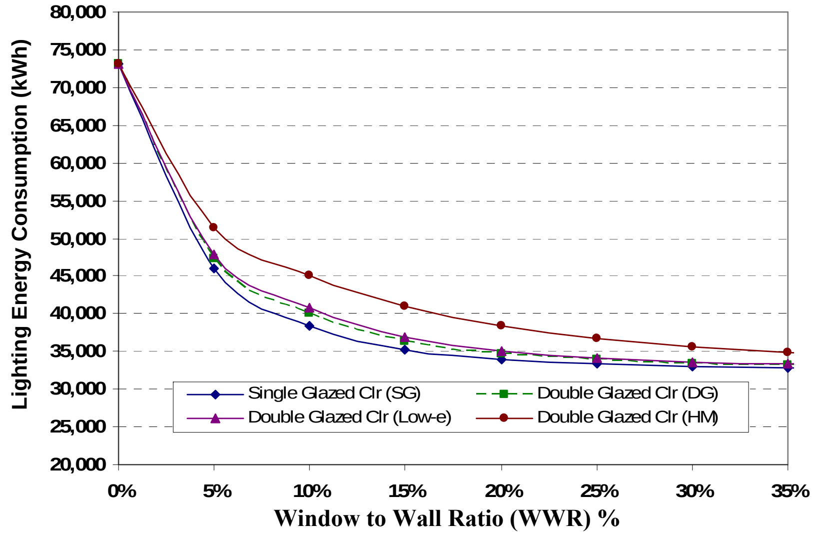

**Lighting energy consumption for various glazing types- 1.55m window height- North zone**



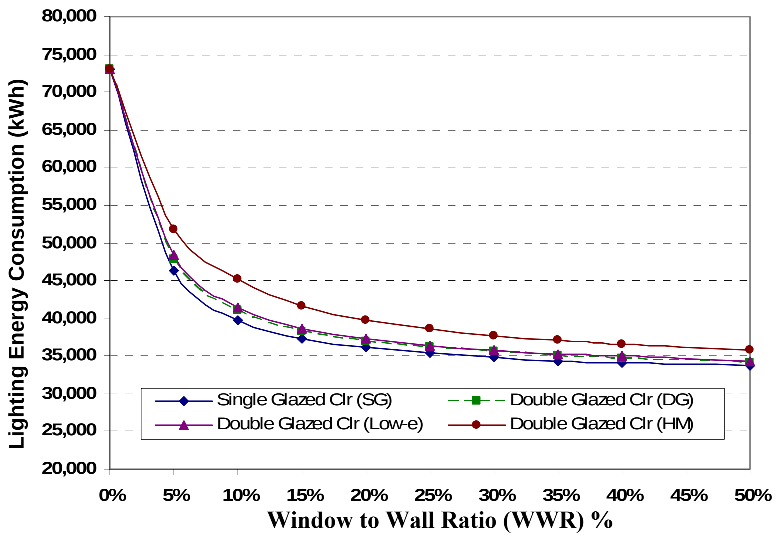

**Lighting energy consumption for various glazing types- 1.55m window height- East zone**



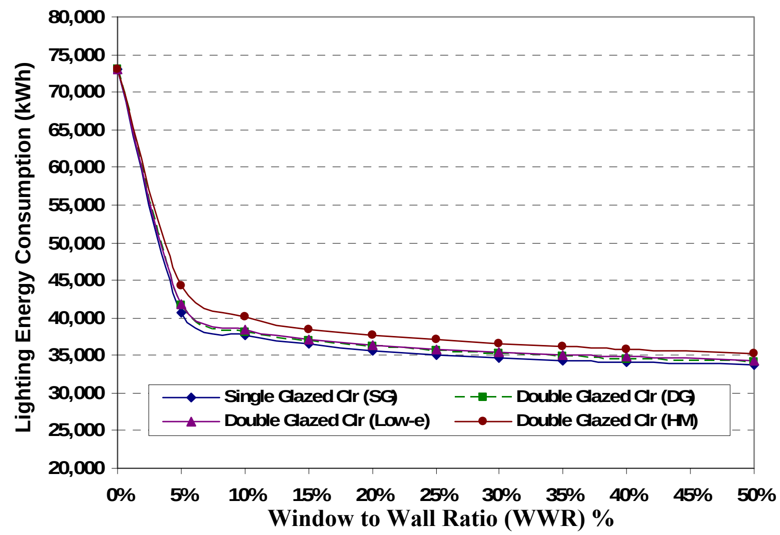

**Lighting energy consumption for various glazing types- 1.55m window height- South zone**



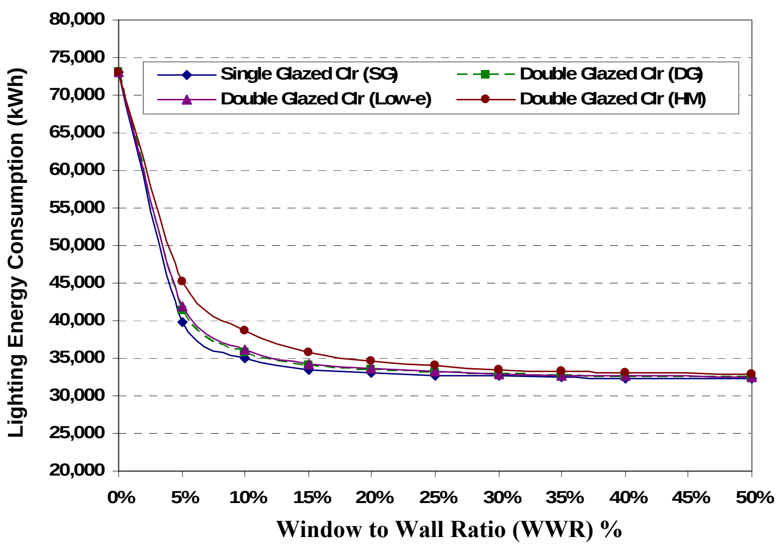

**Lighting energy consumption for various glazing types- 1.55m window height- West zone**



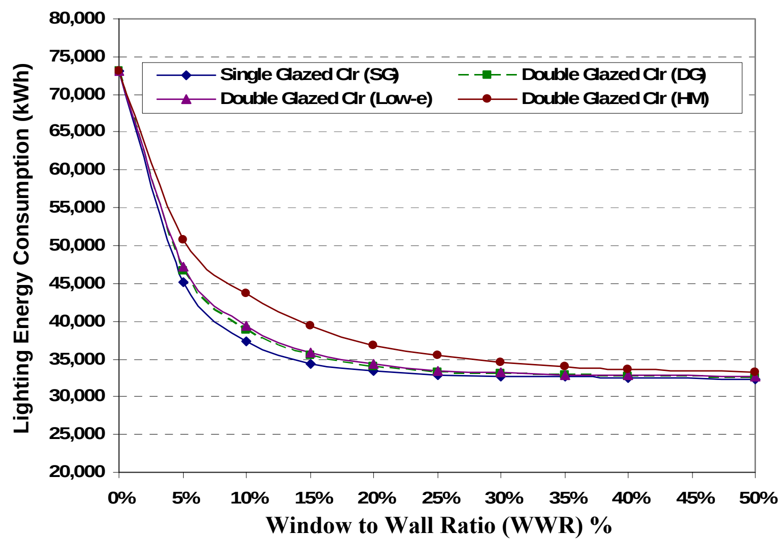

**Lighting energy consumption for various glazing types-1.90m window height- North zone**



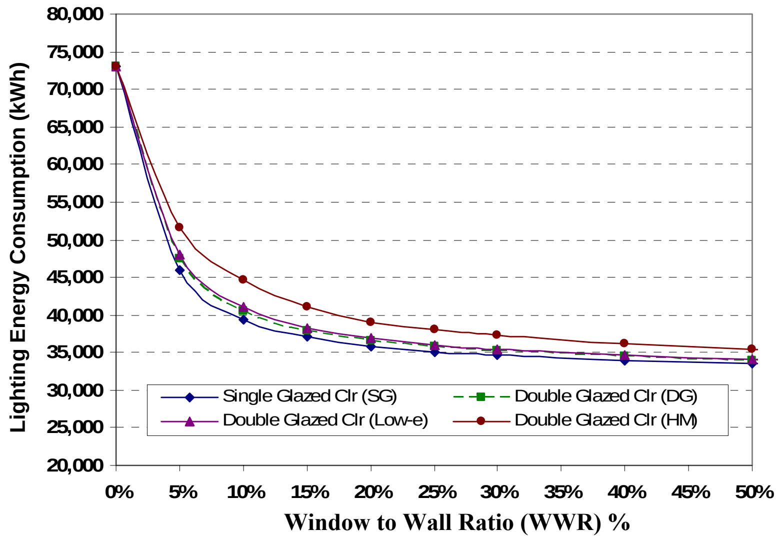

**Lighting energy consumption for various glazing types-1.90m window height- East zone**



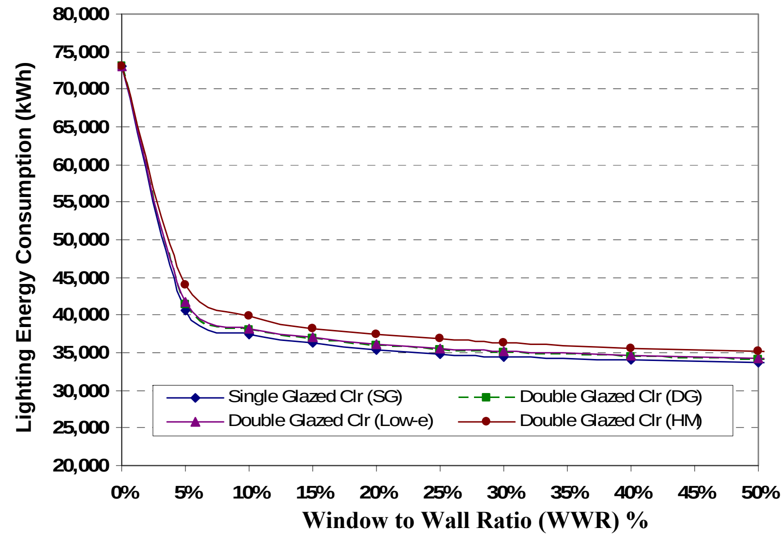

**Lighting energy consumption for various glazing types-1.90m window height- South zone**



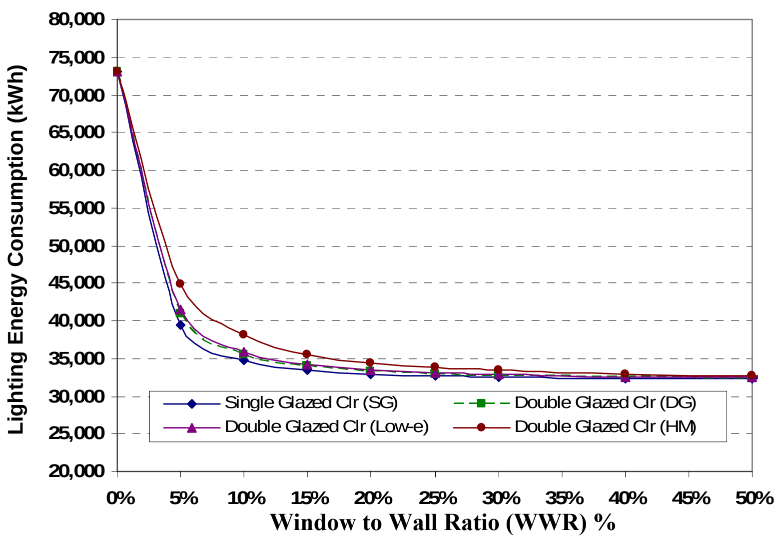

**Lighting energy consumption for various glazing types-1.90m window height- West zone**



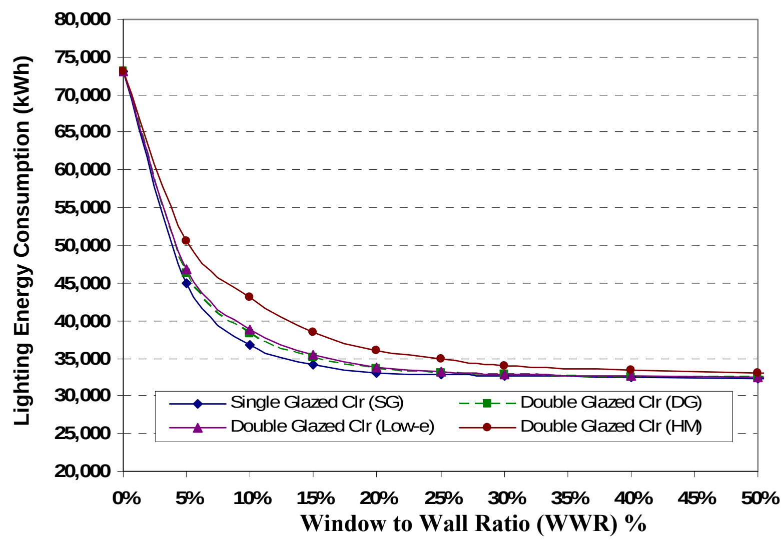

**Lighting energy consumption for various glazing types- 2.25m window height- North zone**



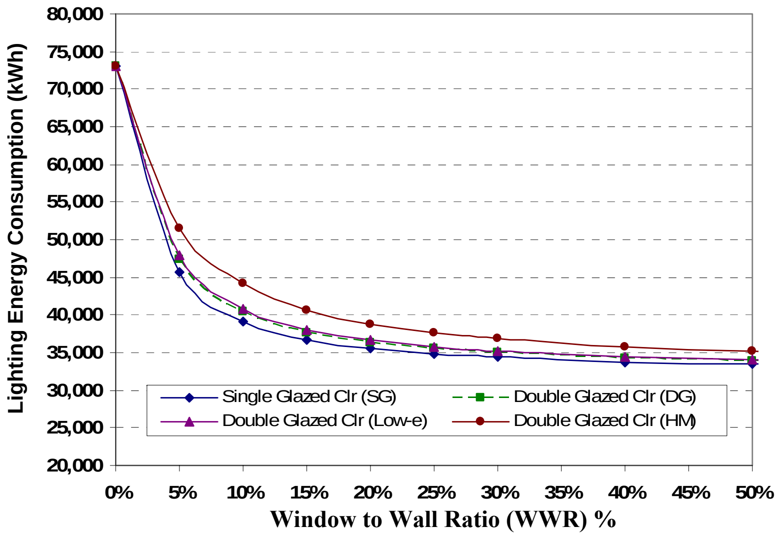

**Lighting energy consumption for various glazing types- 2.25m window height- East zone**



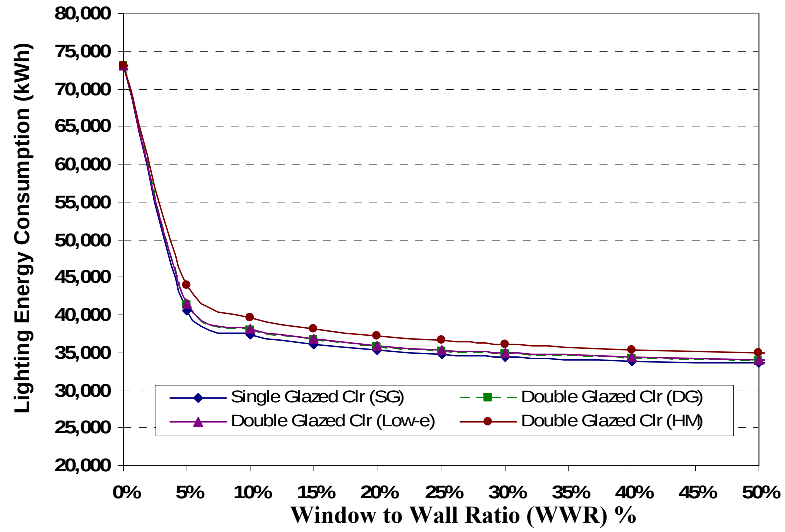

**Lighting energy consumption for various glazing types- 2.25m window height- South zone**



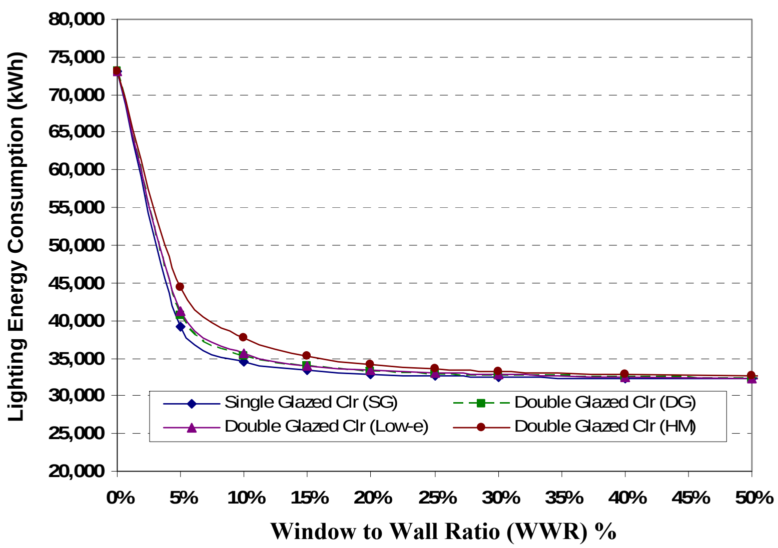

**Lighting energy consumption for various glazing types- 2.25m window height- West zone**



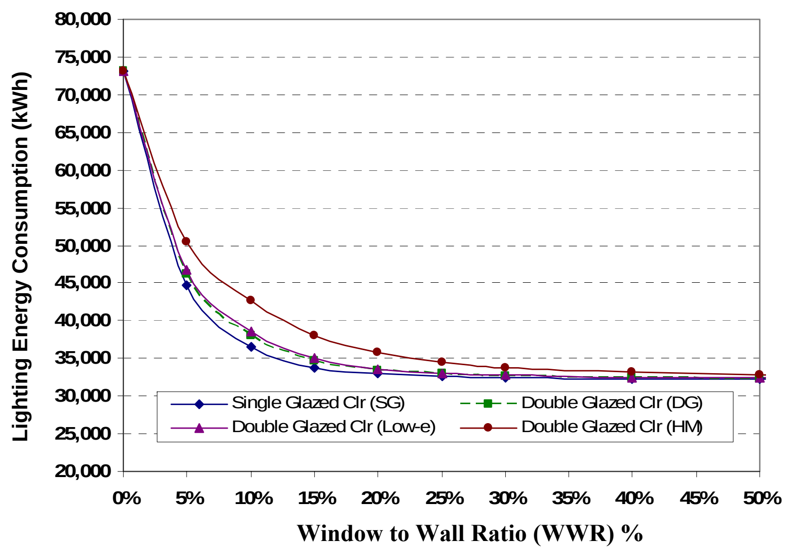

**Lighting energy consumption for various glazing types- 2.60m window height- North zone**




**Lighting energy consumption for various glazing types- 2.60m window height- East zone**

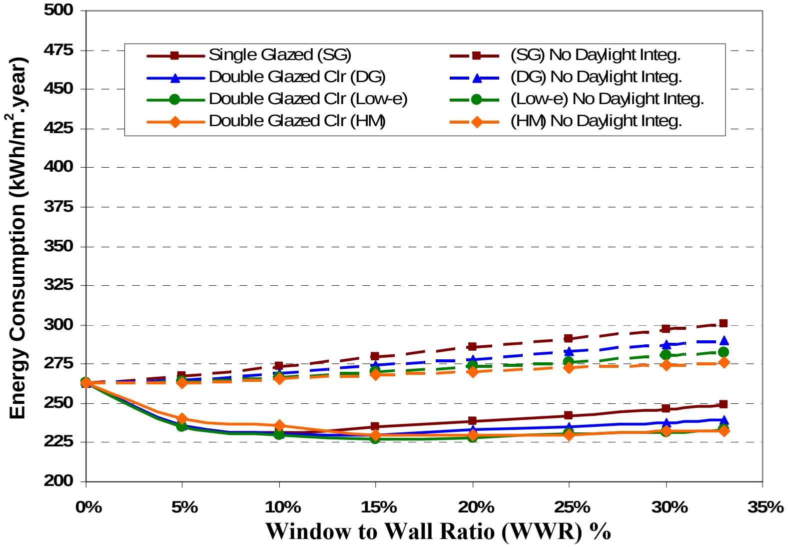



**Lighting energy consumption for various glazing types- 2.60m window height- South zone**

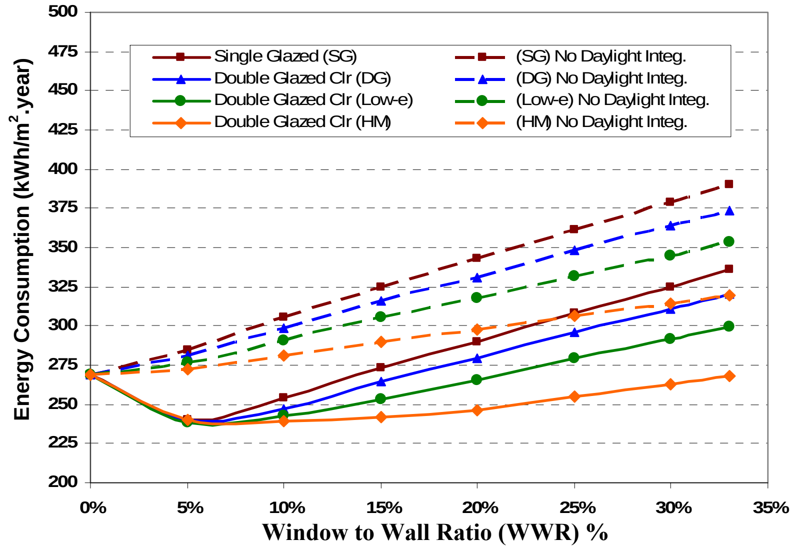



**Lighting energy consumption for various glazing types- 2.60m window height- West zone**

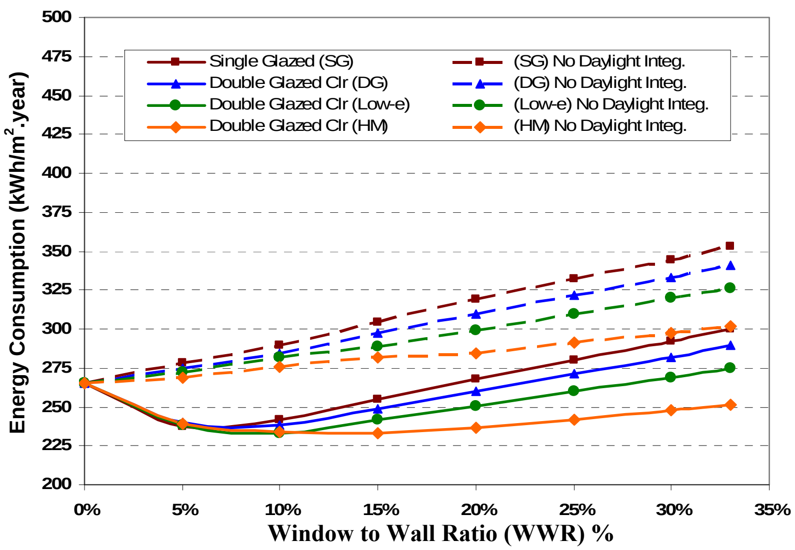
## APPENDIX D: Total Energy Consumption for Various Glazing Types – Various Window Heights – Principal Zone Orientations



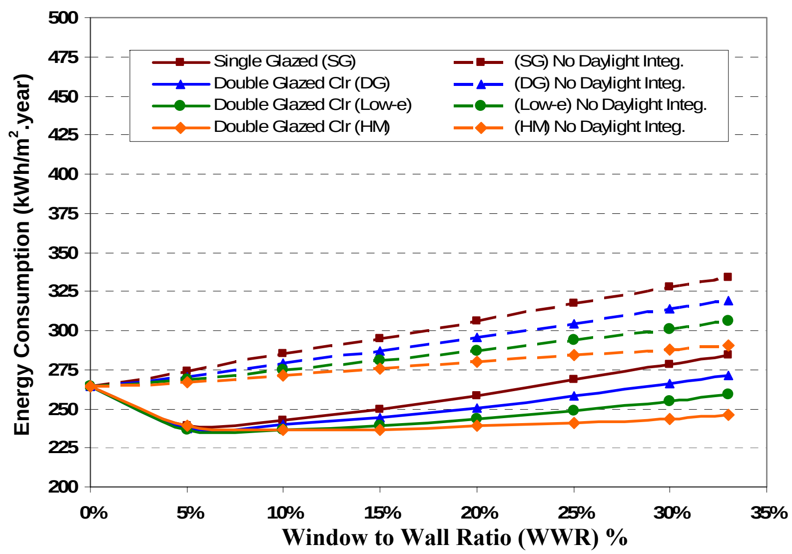

**Total energy consumption for various glazing types-1.20m window height-North zone**



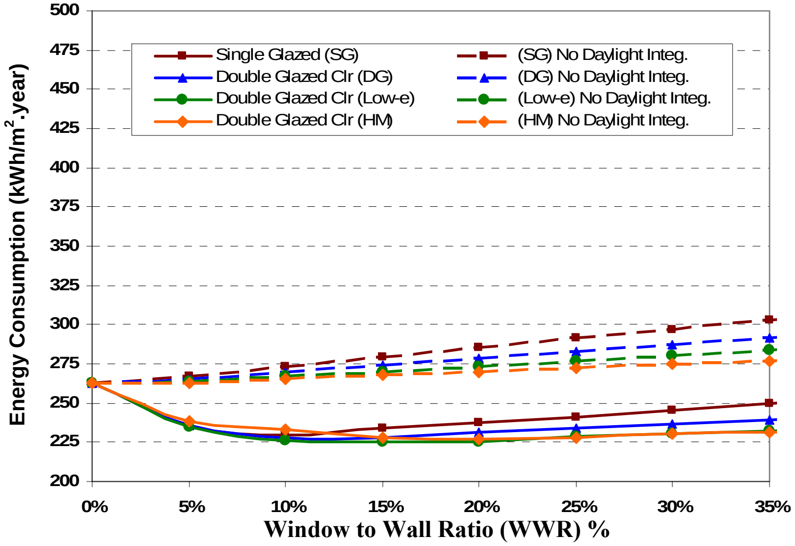

**Total energy consumption for various glazing types-1.20m window height-East zone**



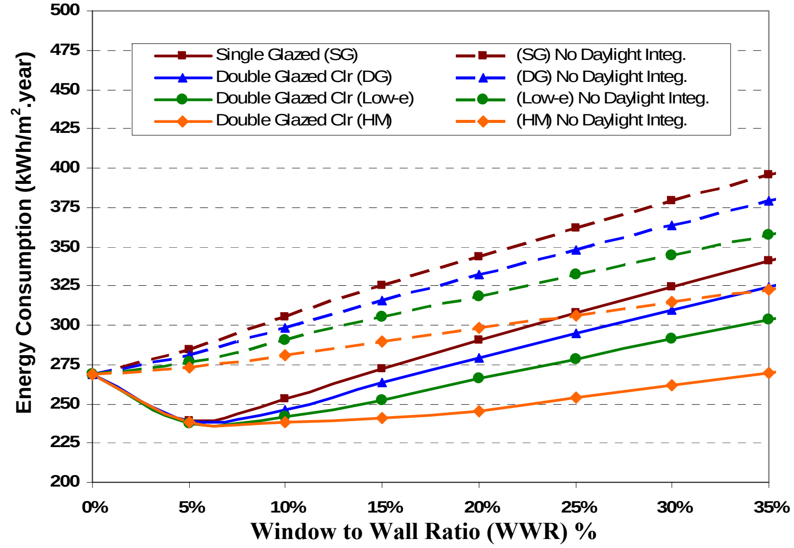

**Total energy consumption for various glazing types-1.20m window height-South zone**



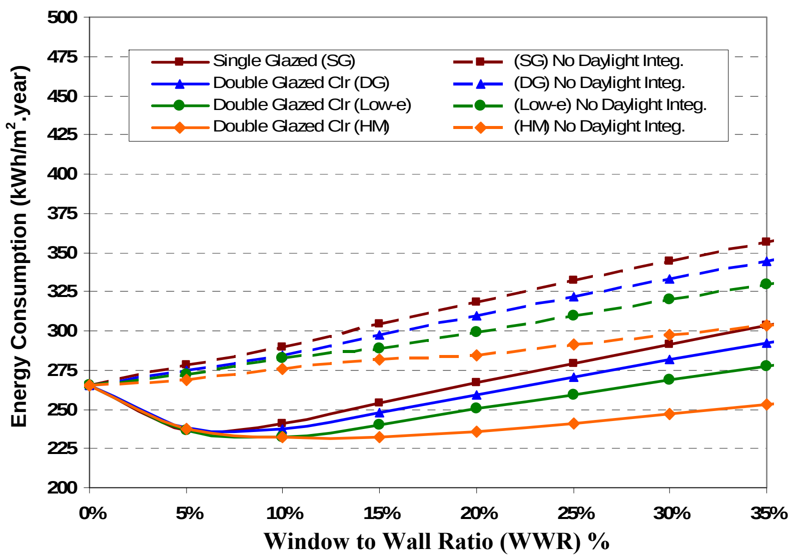

**Total energy consumption for various glazing types-1.20m window height-West zone**



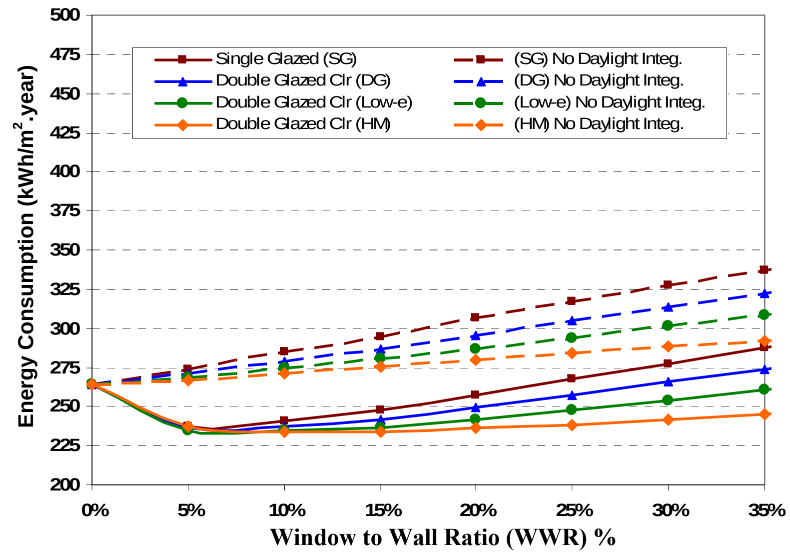

**Total energy consumption for various glazing types-1.55m window height-North zone**



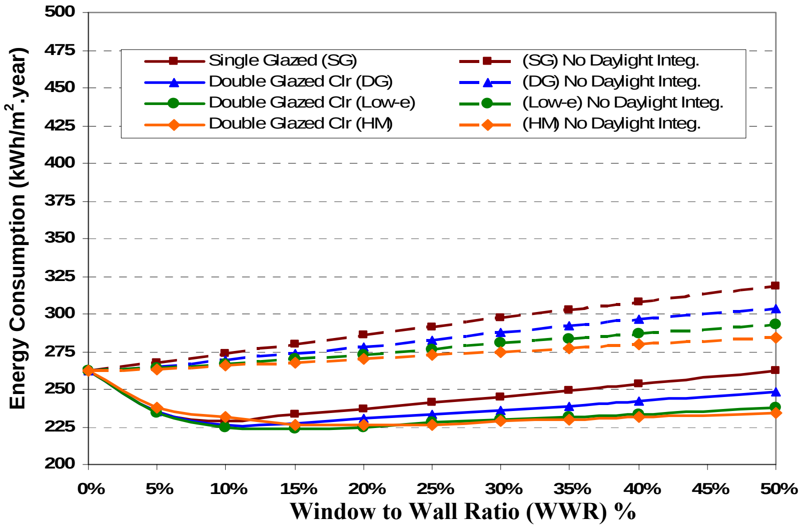

**Total energy consumption for various glazing types-1.55m window height-East zone**



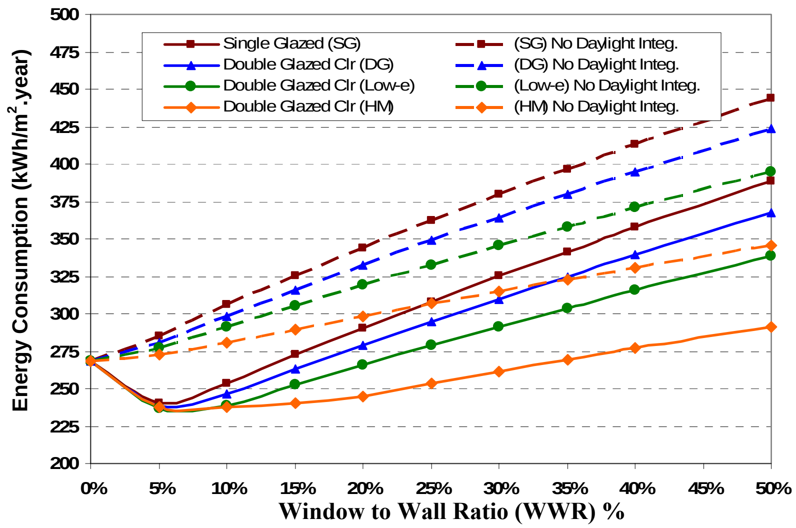

**Total energy consumption for various glazing types-1.55m window height-South zone**



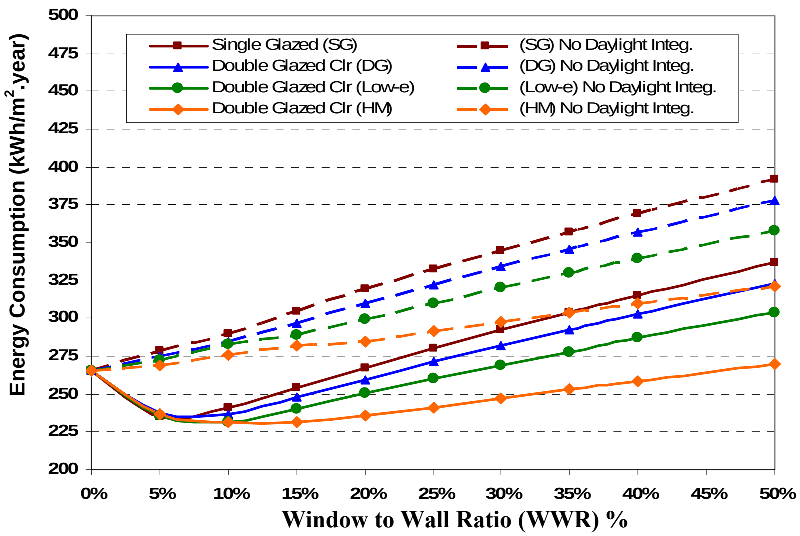

**Total energy consumption for various glazing types-1.55m window height-West zone**



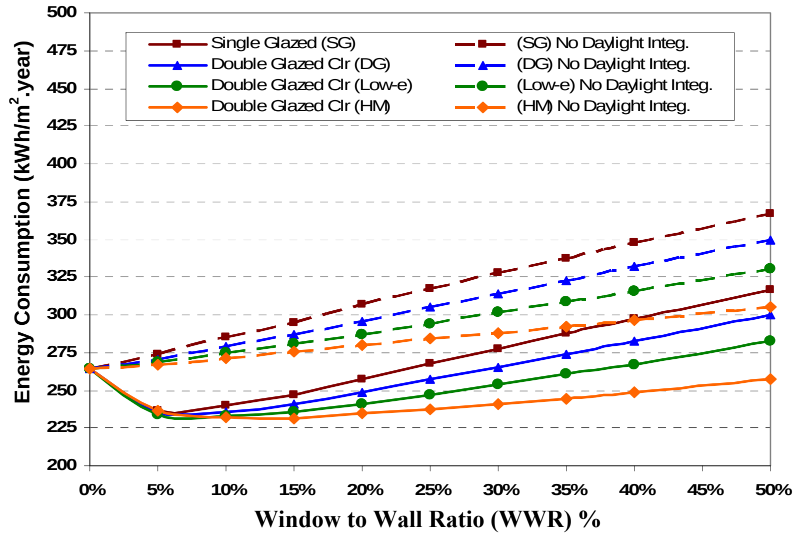

**Total energy consumption for various glazing types-1.90m window height-North zone**



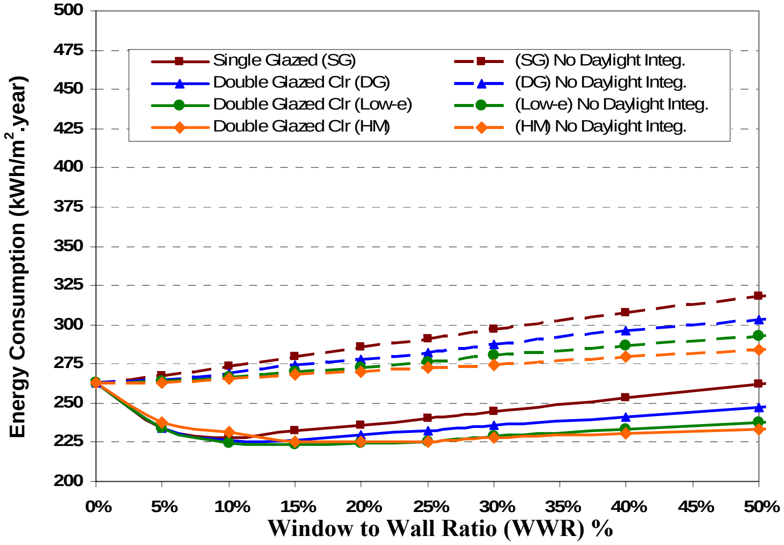

**Total energy consumption for various glazing types-1.90m window height-East zone**



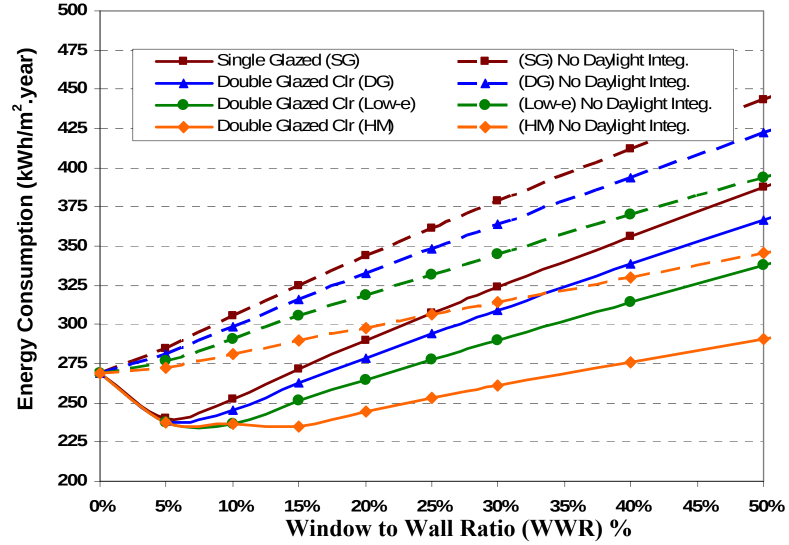

**Total energy consumption for various glazing types-1.90m window height-South zone**



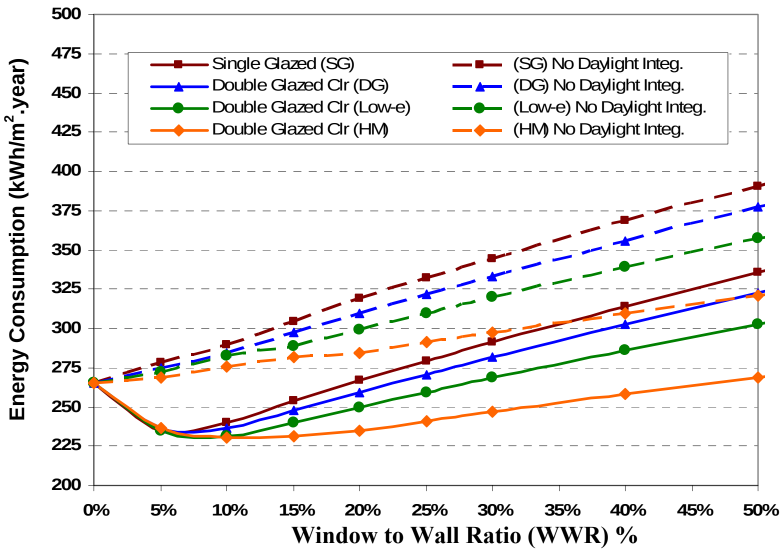

**Total energy consumption for various glazing types-1.90m window height-West zone**



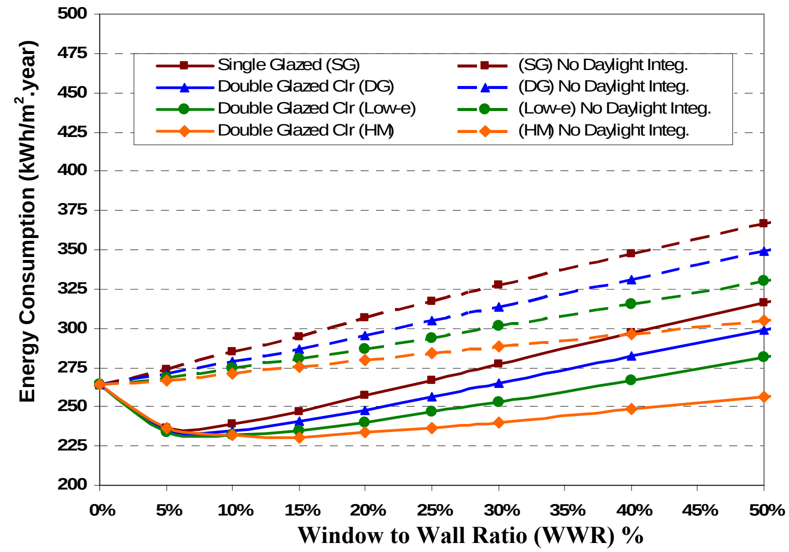

**Total energy consumption for various glazing types-2.25m window height-North zone**



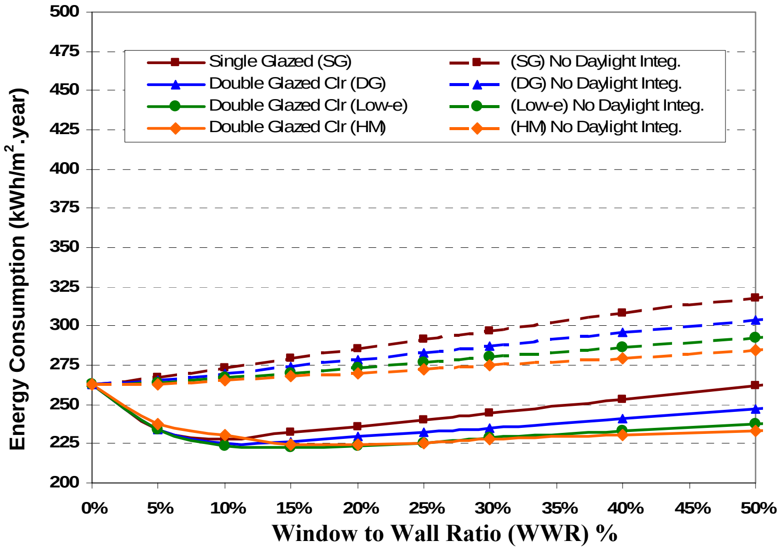

**Total energy consumption for various glazing types-2.25m window height-East zone**



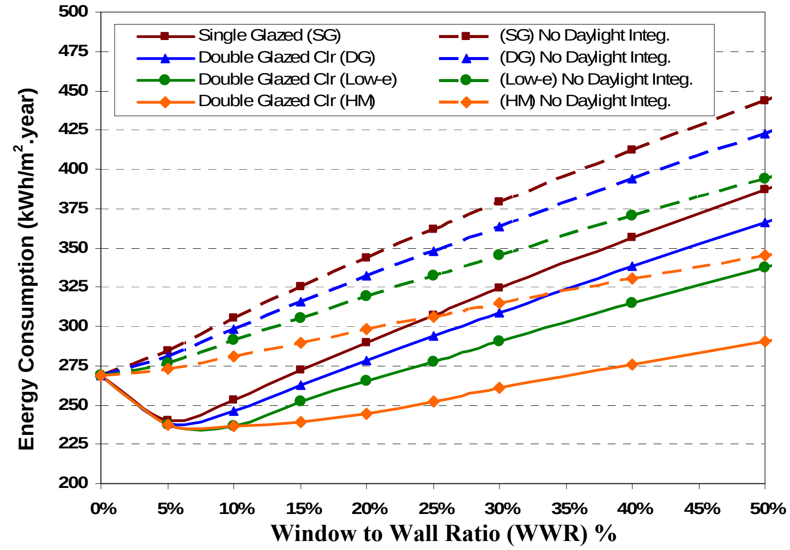

**Total energy consumption for various glazing types-2.25m window height-South zone**



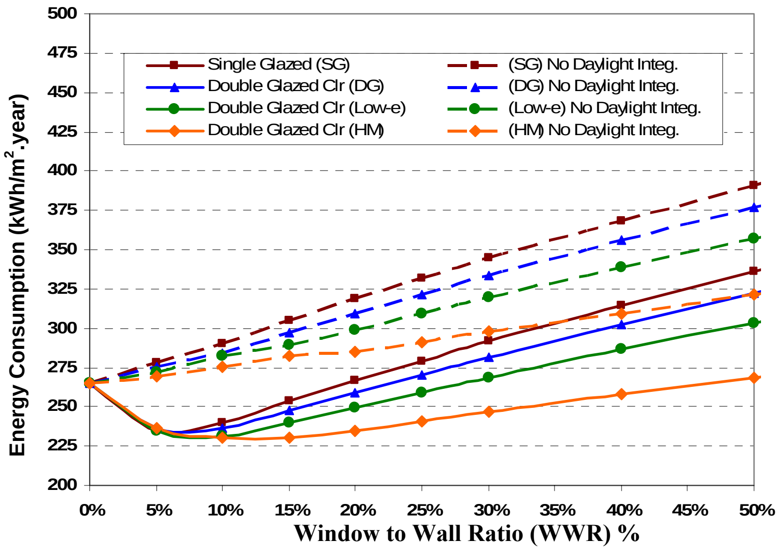

**Total energy consumption for various glazing types-2.25m window height-West zone**



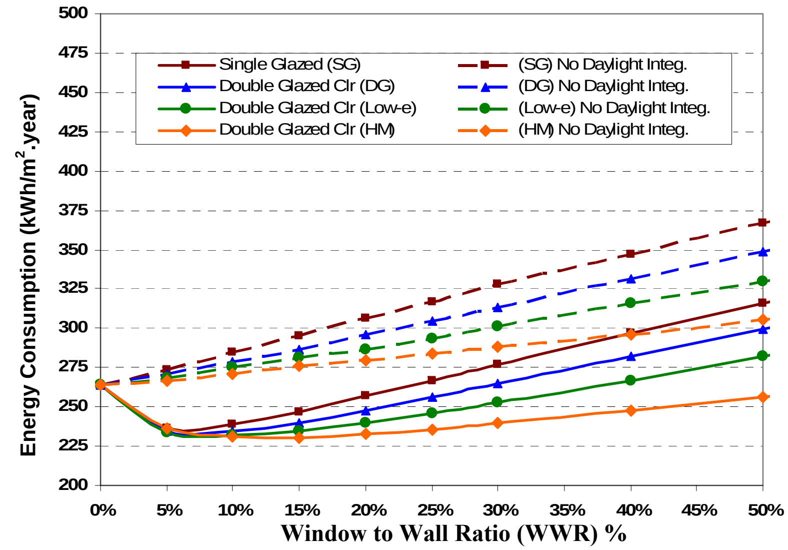

**Total energy consumption for various glazing types-2.60m window height-North zone**




**Total energy consumption for various glazing types-2.60m window height-East zone**

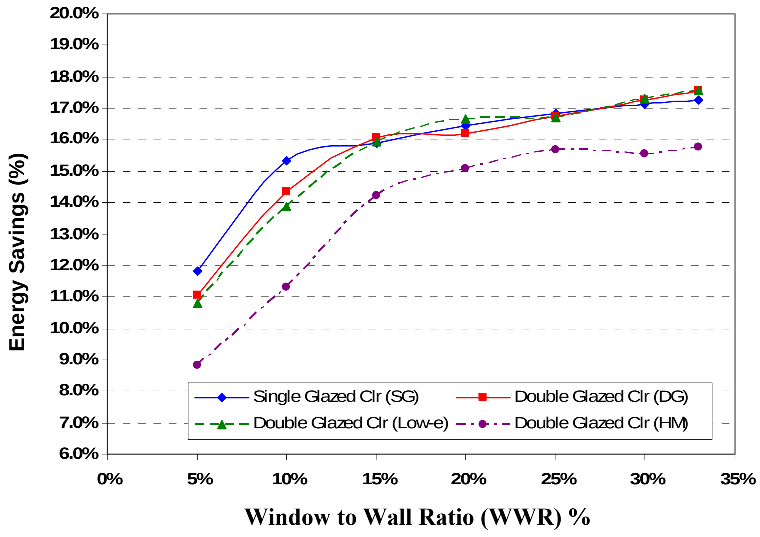



**Total energy consumption for various glazing types-2.60m window height-South zone**

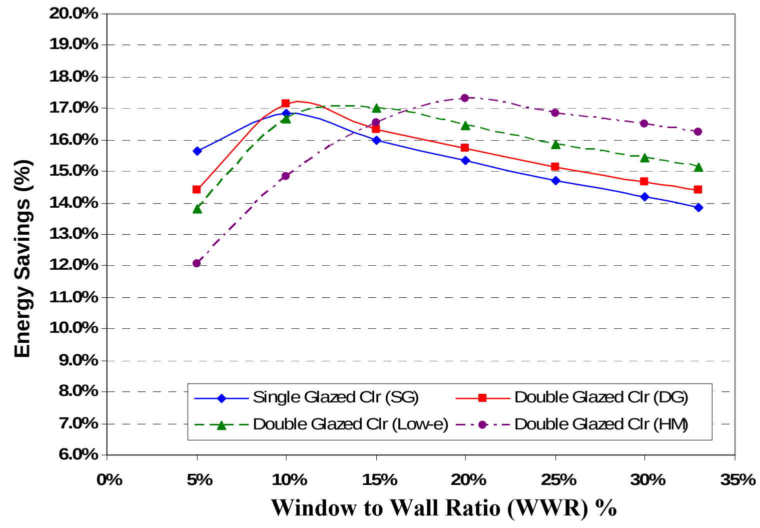



**Total energy consumption for various glazing types-2.60m window height-West zone**

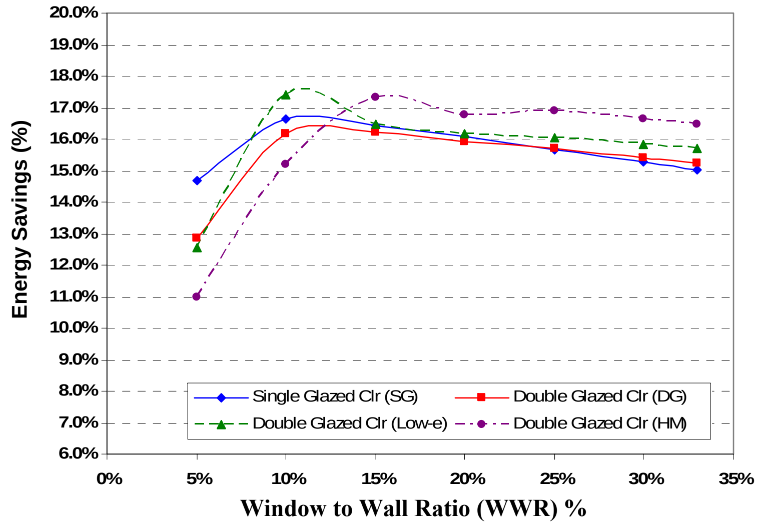
## APPENDIX E: Total Energy Savings for Various Glazing Types – Various Window Heights – Principal Zone Orientations



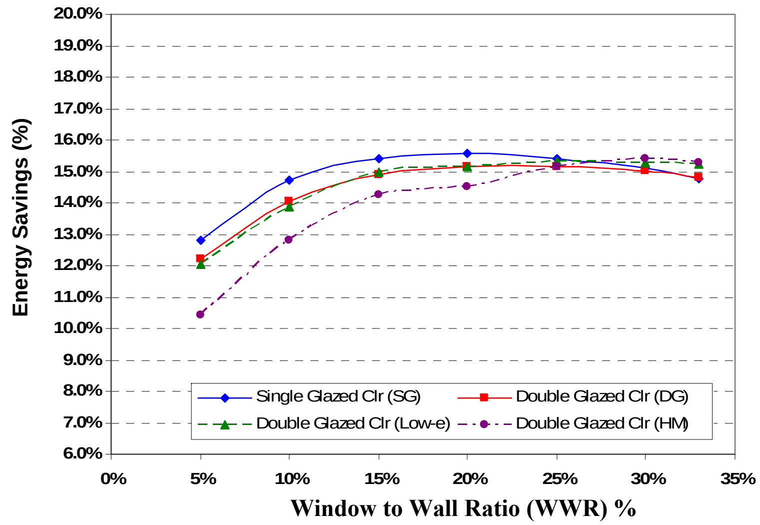

**Total energy savings for various glazing types-1.20m window height-North zone**



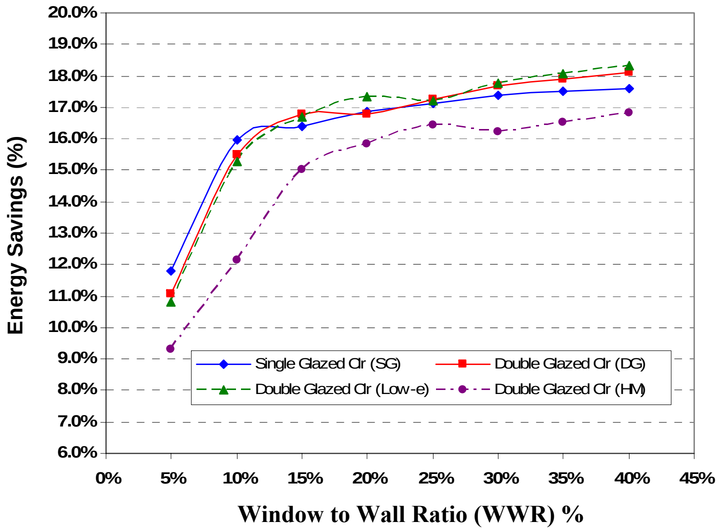

**Total energy savings for various glazing types-1.20m window height-East zone**



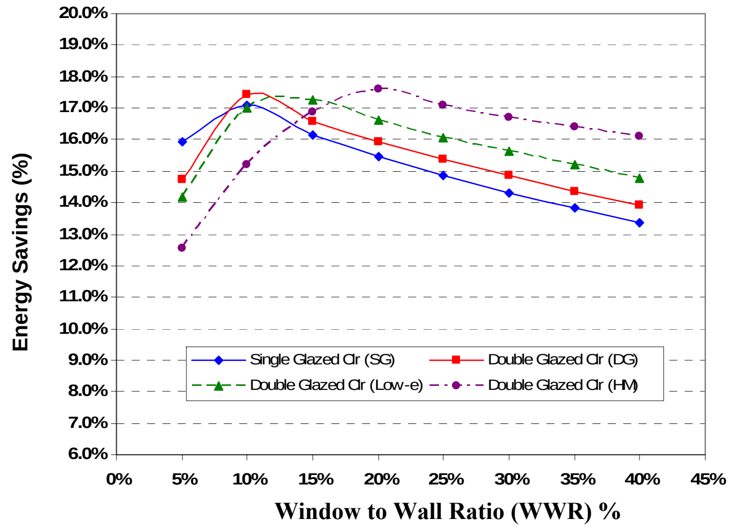

**Total energy savings for various glazing types-1.20m window height-South zone**



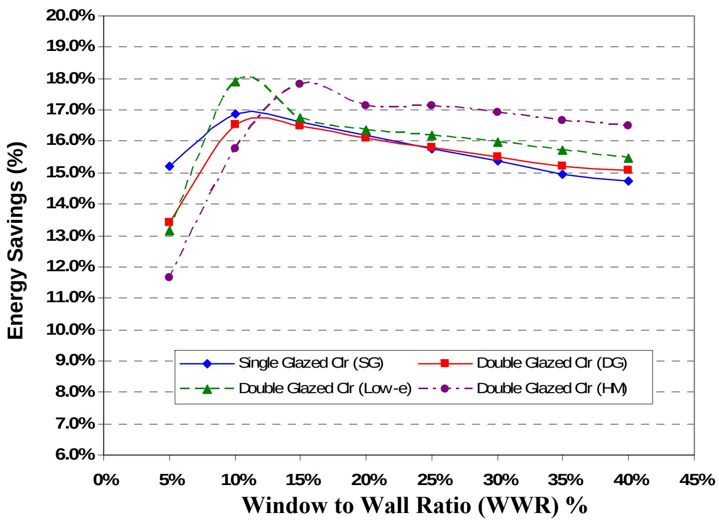

**Total energy savings for various glazing types-1.20m window height-West zone**



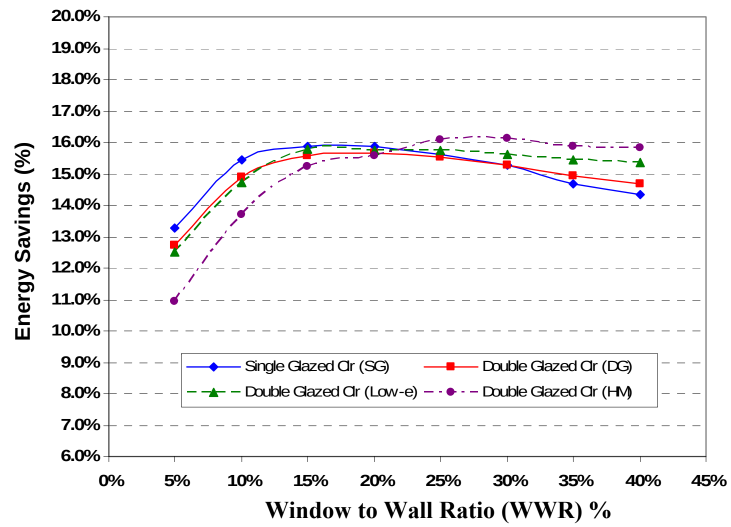

**Total energy savings for various glazing types-1.55m window height-North zone**



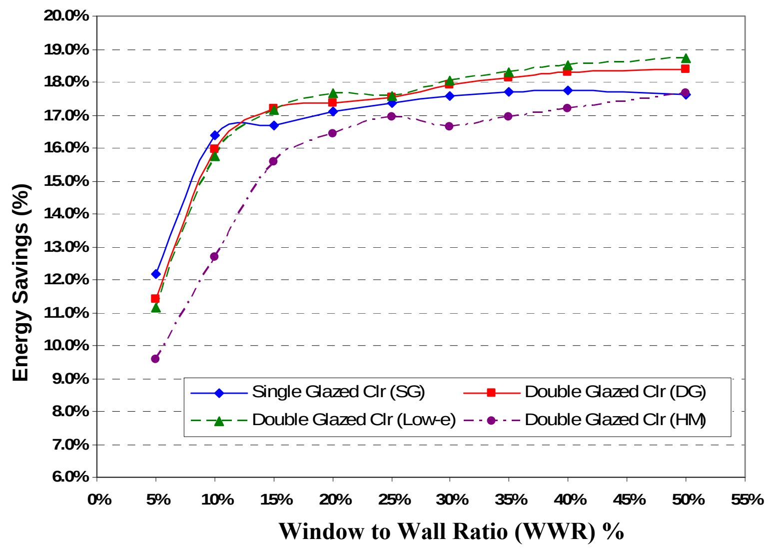

**Total energy savings for various glazing types-1.55m window height-East zone**



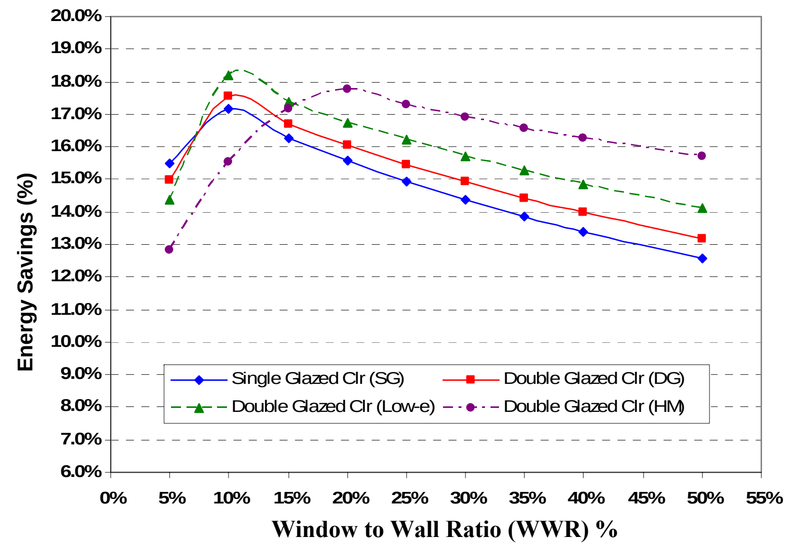

**Total energy savings for various glazing types-1.55m window height-South zone**



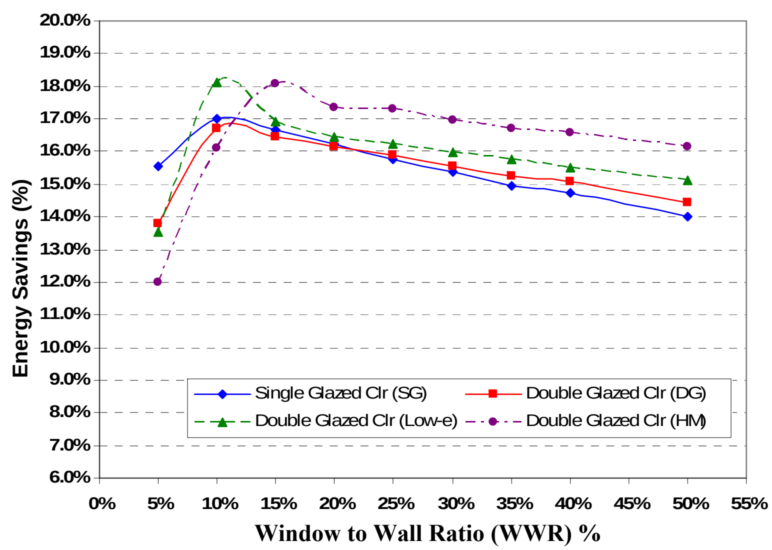

**Total energy savings for various glazing types-1.55m window height-West zone**



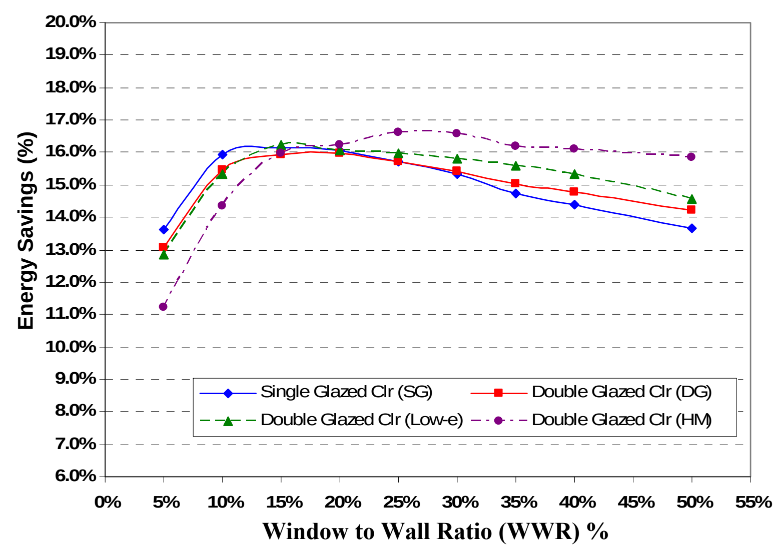

**Total energy savings for various glazing types-1.90m window height-North zone**



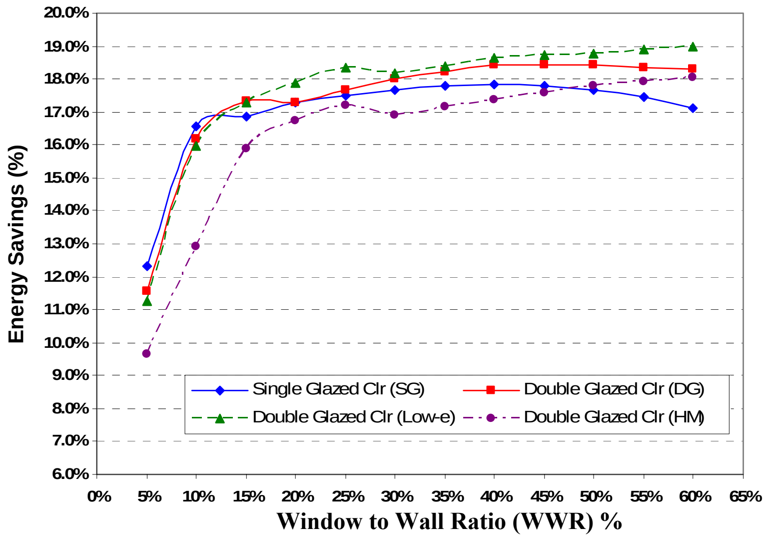

**Total energy savings for various glazing types-1.90m window height-East zone**



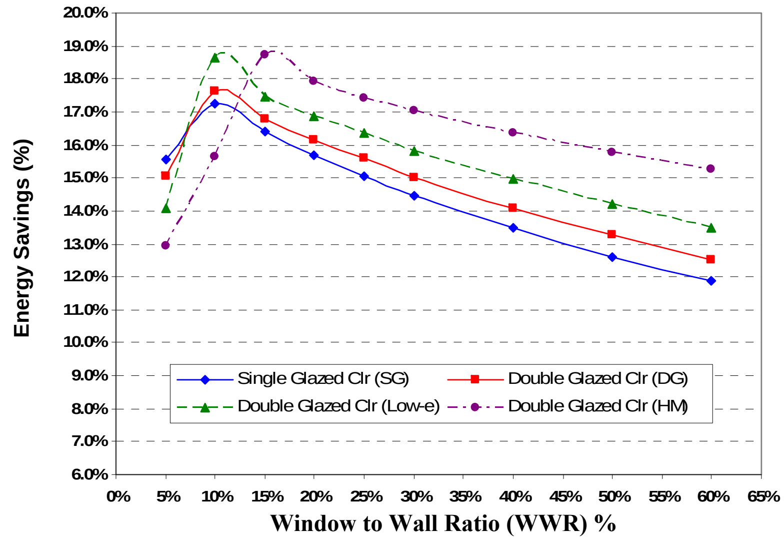

**Total energy savings for various glazing types-1.90m window height-South zone**



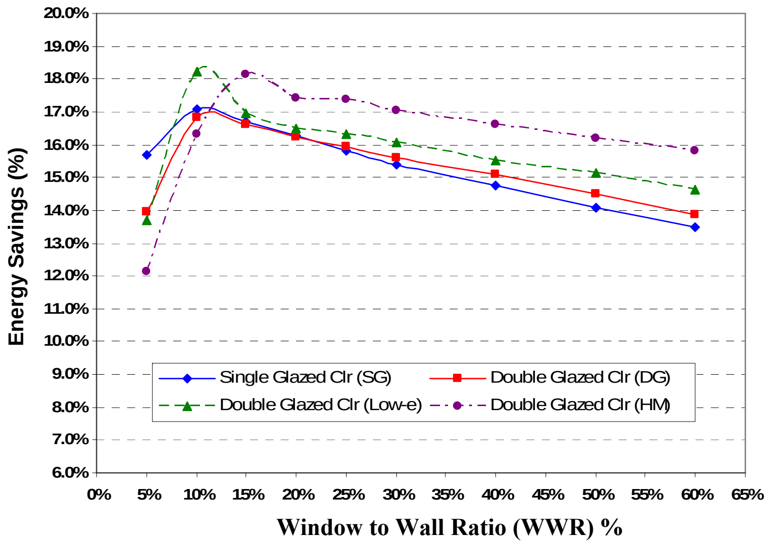

**Total energy savings for various glazing types-1.90m window height-West zone**



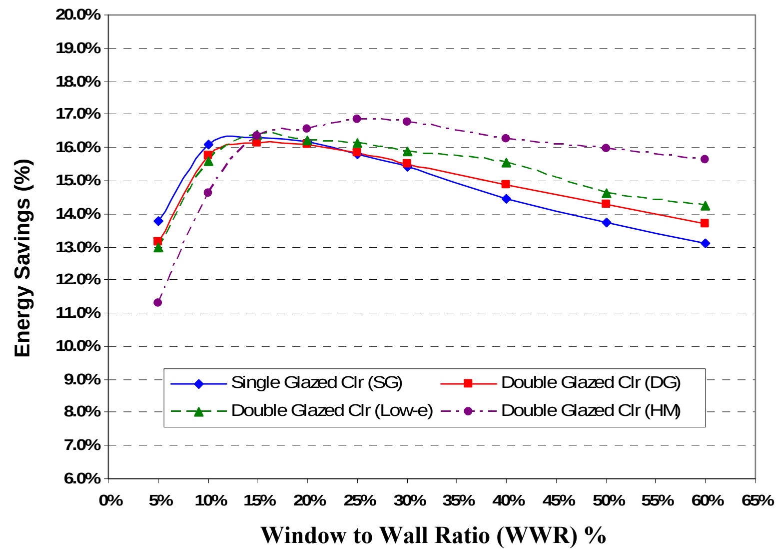

**Total energy savings for various glazing types-2.25m window height-North zone**



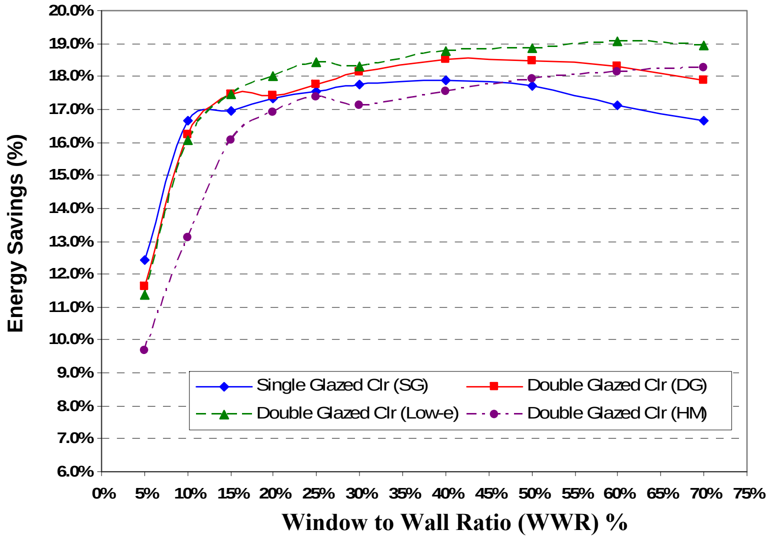

**Total energy savings for various glazing types-2.25m window height-East zone**



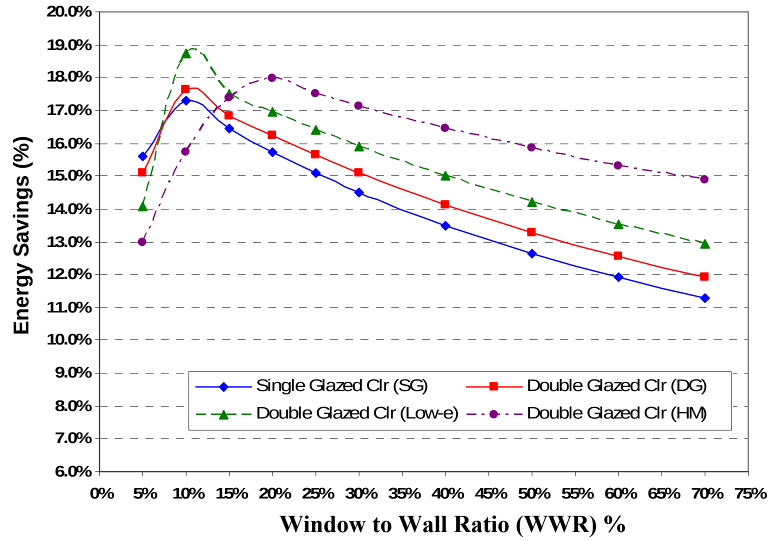

**Total energy savings for various glazing types-2.25m window height-South zone**



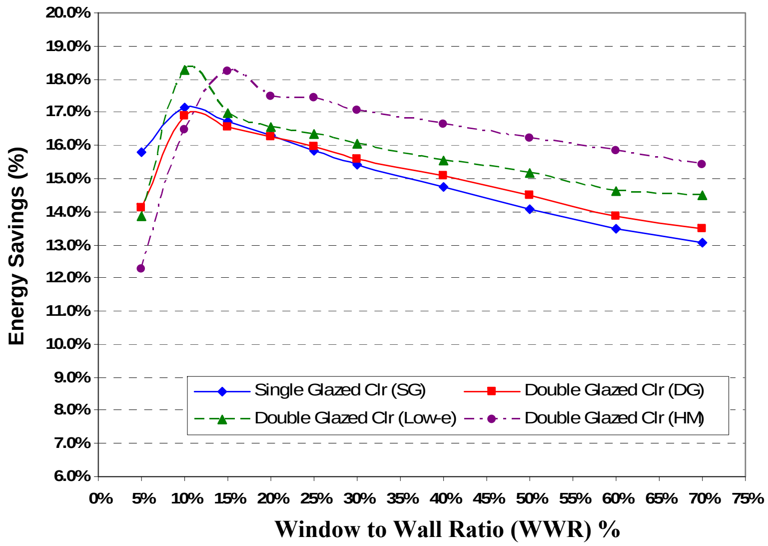

**Total energy savings for various glazing types-2.25m window height-West zone**



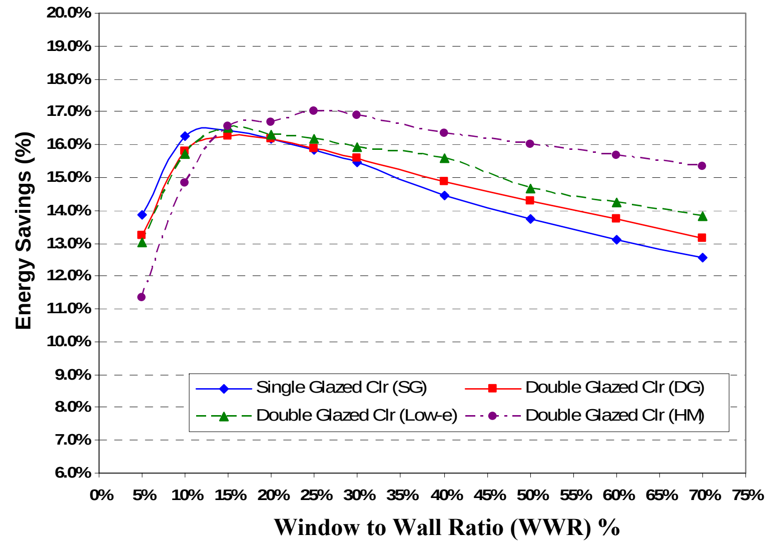

**Total energy savings for various glazing types-2.60m window height-North zone**




**Total energy savings for various glazing types-2.60m window height-East zone**




**Total energy savings for various glazing types-2.60m window height-South zone**




**Total energy savings for various glazing types-2.60m window height-West zone**

# VITAE

| | |
|---|---|
| Name | : Nagib Taher Ahmed Al-Ashwal |
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| | : **BACHELOR OF ENGINEERING**<br>Sana'a University, Sana'a, Republic of Yemen<br>Cumulative GPA 84.01% |
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